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Full-scale Experimental Validation of Dynamic, Centrifugally Powered, Pneumatic Actuators for Active Rotor Blade Surfaces

Dr. Joseph Szefi, President

Invercon, LLC

Luke Ionno, Aeronautical Engineer

Brian Cormier, Senior Flight Test & Product Design Engineer

Kaman Aerospace Corporation

NASA Aeronautics Research Mission Directorate (ARMD)

FY12 LEARN Phase I Technical Seminar

November 13-15, 2013

Outline

- Background
- The Innovation:
  - Centrifugally Powered Pneumatic Actuators
- Technical Approach / Results
- Planned Future Work

Background: Active Trailing Edge Flaps for Rotorcraft

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Serious Constraints in Rotorcraft Transportation

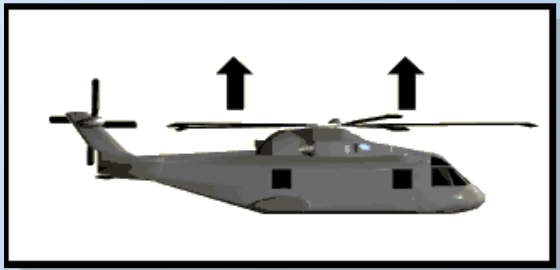
- Poor ride quality due to high levels of vibration
- Noise, restricted flight envelope
- Low fatigue life of structural components and high operation cost

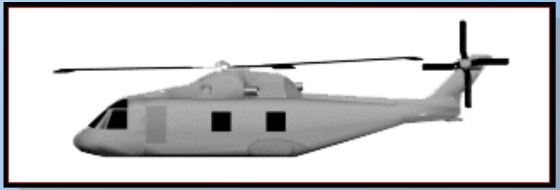
Helicopter vibration sources

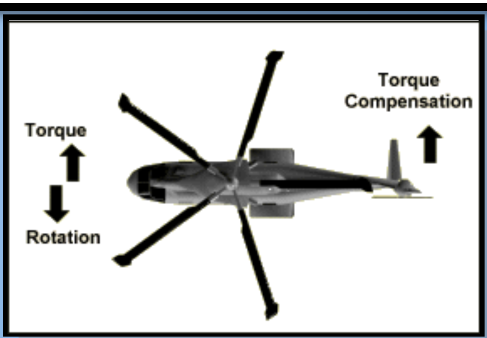
- Main rotor system – Unique feature of helicopter
- Aerodynamic interaction between rotor and fuselage
- Tail rotor, engine and transmission

Active trailing edge flaps may offer active vibration control solution

- Tailor aerodynamics to counteract harmonic and non-harmonic disturbances
- With sufficient actuation levels, flaps may enable swashplateless rotor
  - No mechanical swashplate, reduced rotor complexity







Background: Active Trailing Edge Flaps for Rotorcraft

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Piezoelectric Stack-Based Actuators – Currently Preferred Actuation Approach

- Lee and Chopra (1999-2001): double-lever and bi-directional double-lever actuators
- Straub and Kennedy (2007): Double X-Frame actuator, Boeing
- Leconte and Hofinger (2004): ONERA, DLR, Eurocopter

Boeing - Double X-Frame Trailing Edge Flap Actuator

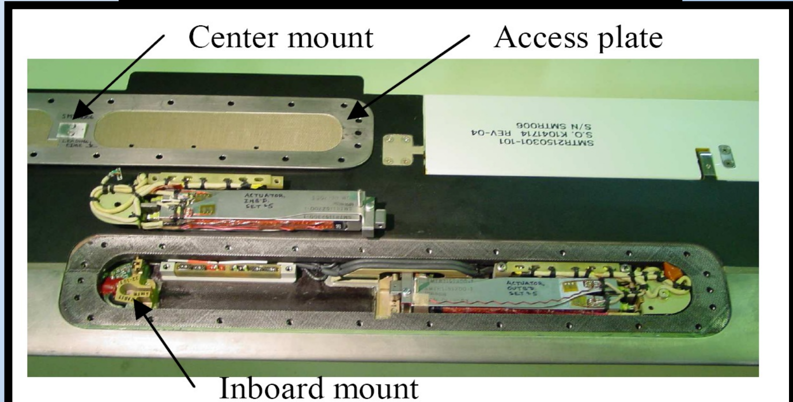
- Whirl tested by Boeing in a fully instrumented MD 900 Explorer rotor in 2007

Eurocopter – Adaptive Dynamic System (ADASYS)

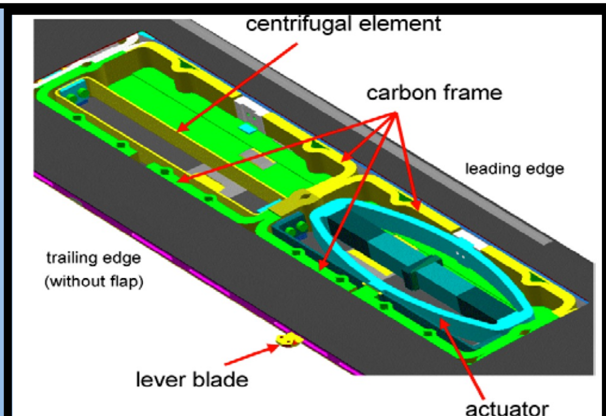
- Flight tested by Eurocopter in BK117 in 2005

Drawbacks: Added blade weight, complex mechanical motion amplifiers, high voltage slip rings, and no more than ±3º

Double X-Frame Actuator



Eurocopter ADASYS Actuator



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Centrifugally Generated Pressure Differentials for Actuation

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Pressure Differential Created Across Two Hollow Tubes that Span the Blade

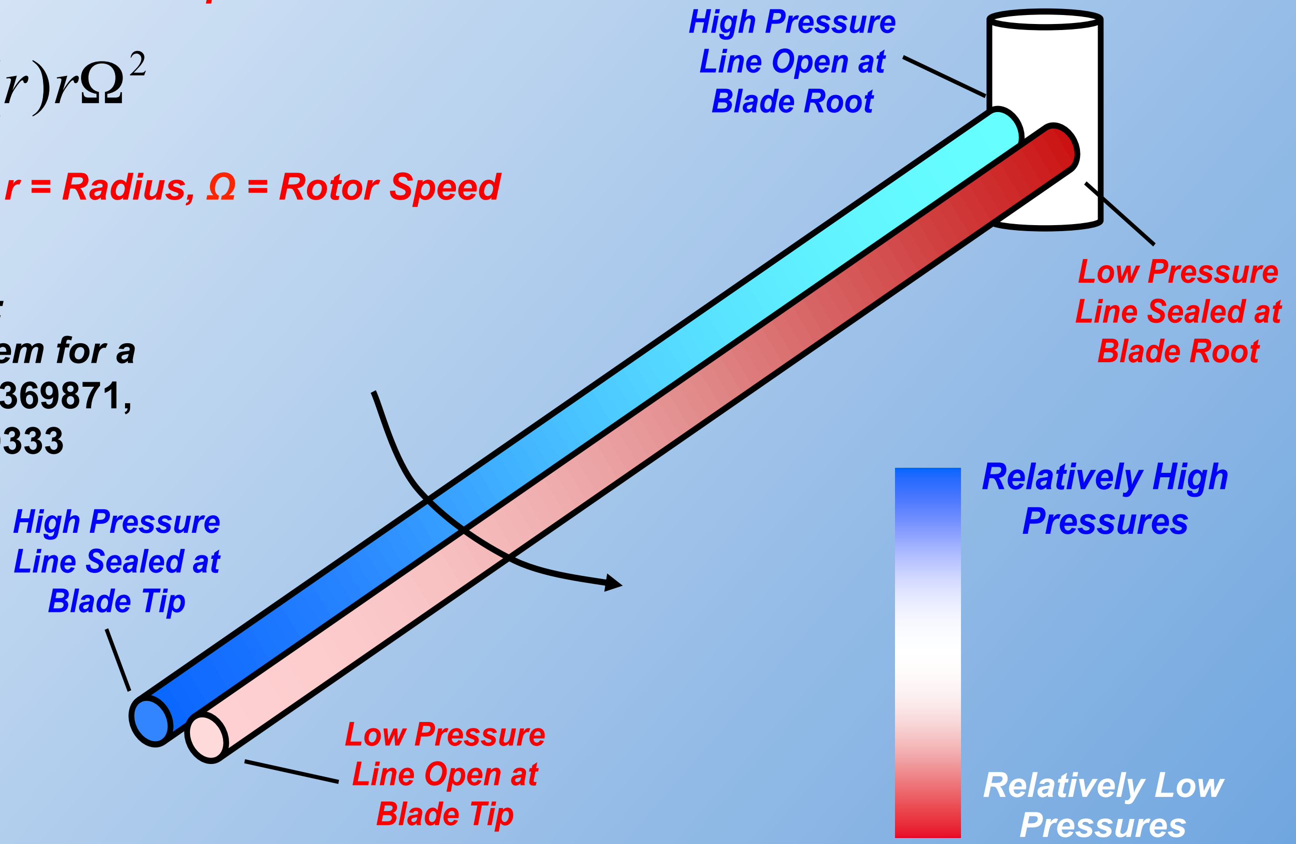
A Pressure Differential of ~7 psi Available for Actuation Along Entire Blade Length for K-MAX

Analysis based on hydrostatic equation:

$$\frac{dp}{dr} = \rho(r) r \Omega^2$$

p = Pressure, ρ = Density, r = Radius, Ω = Rotor Speed

Patented by Invercon LLC:
"Pneumatic Actuator System for a Rotating Blade"**, EFS ID: 9369871,**
Application Number:13020333



Previous Testing: Full Scale Pressure Generation Test at Kaman

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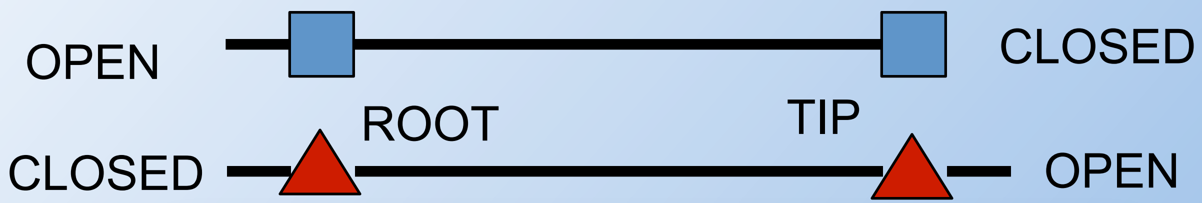
Full-Scale Rotor Test
Pressure Differential Experimentally Demonstrated: 7.5 PSI

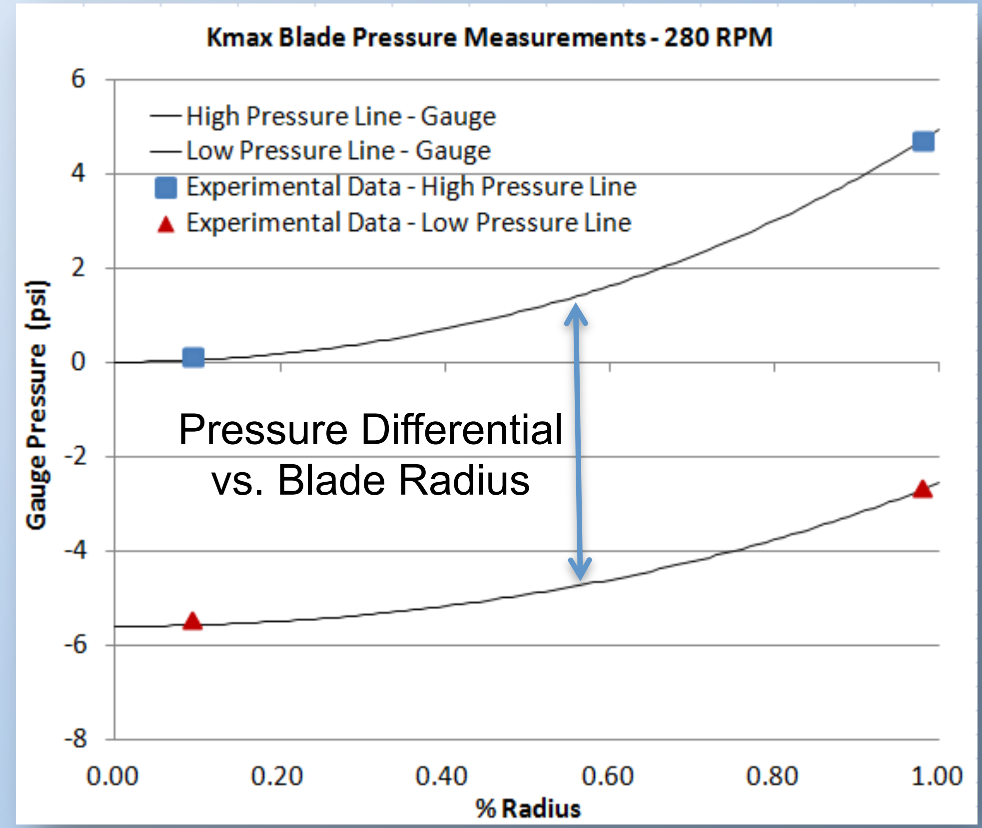
2 Pressure Sensors on Root

2 Pressure Sensors on Tip

280 RPM, 24 ft. Radius Rotor

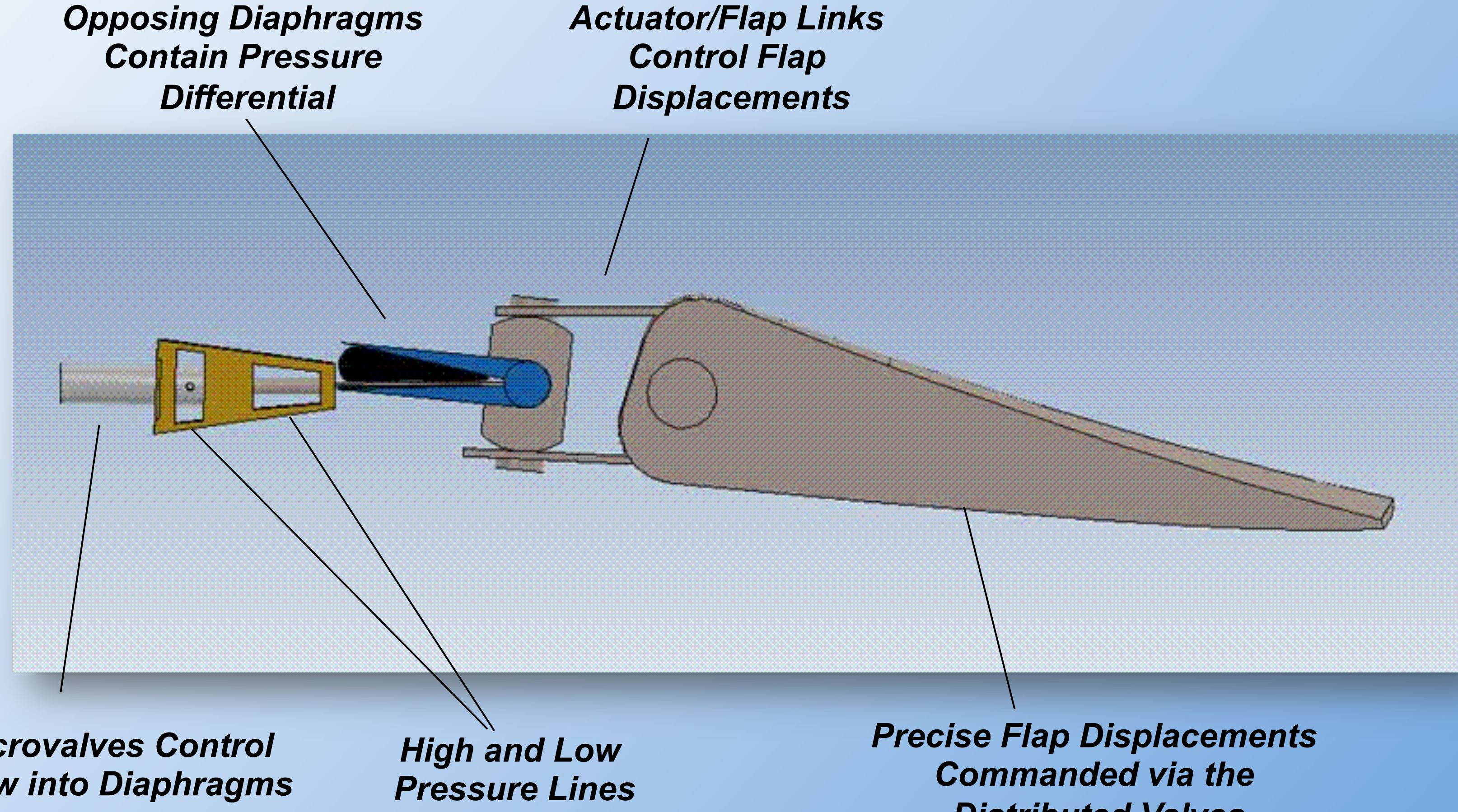
Previous Testing: Full Scale Pressure Generation Test at Kaman





Innovation: Centrifugally Powered Pneumatic Actuators

Early Pneumatic Flap Actuator Design Concept



Innovation: Centrifugally Powered Pneumatic Actuators

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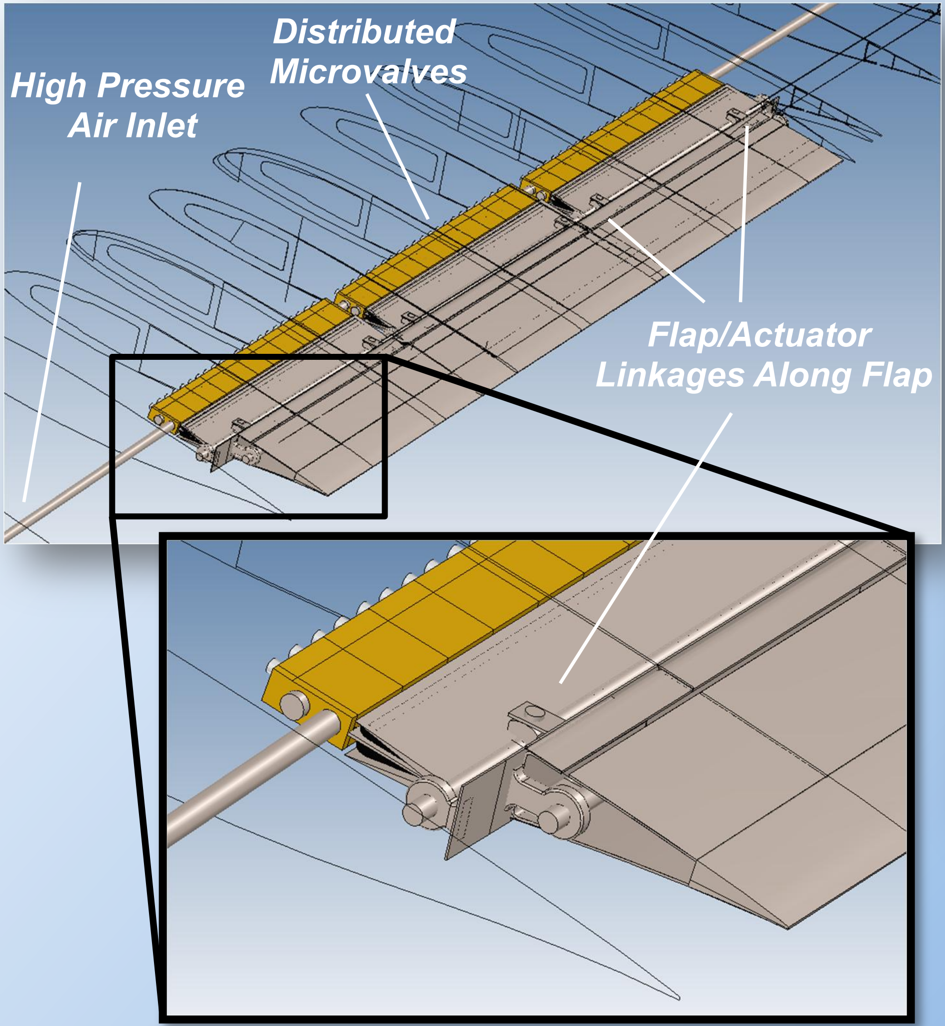
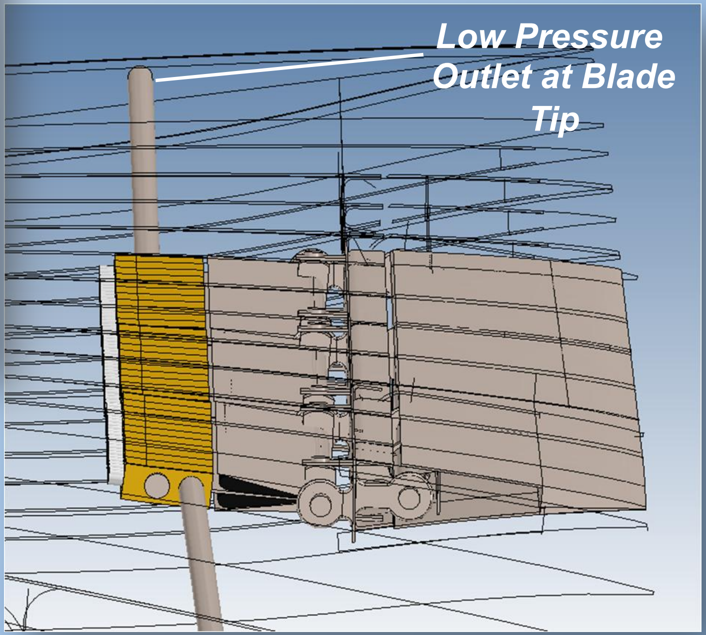


Actuator Co-located Spanwise with Flap



Innovation: Centrifugally Powered Pneumatic Actuators

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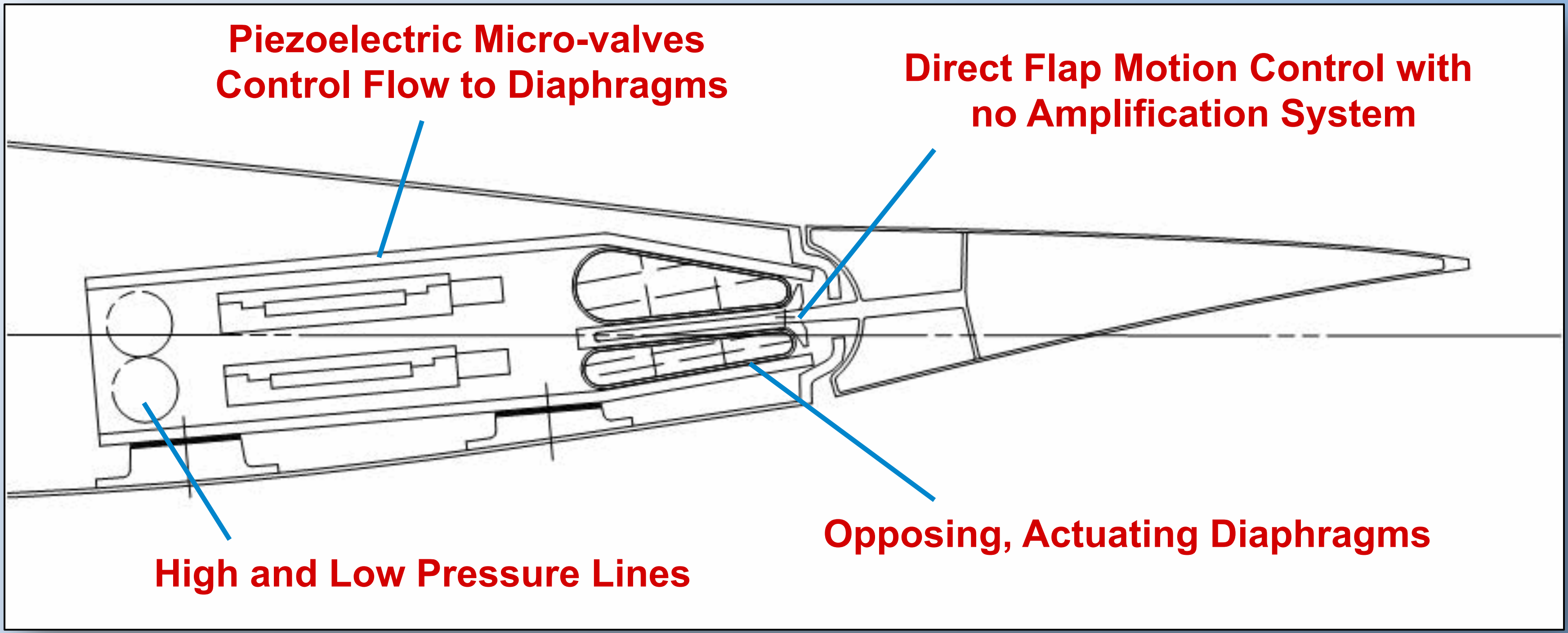
Design Concept Advanced under DARPA’s Mission Adaptive Rotor Program



Outline

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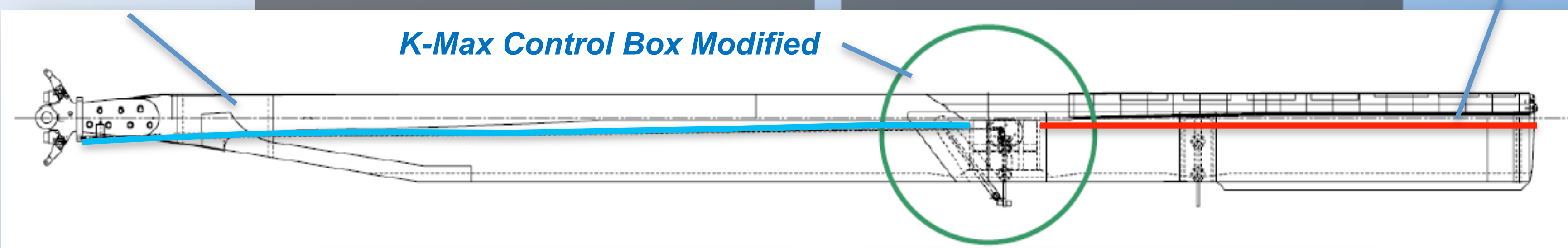
Phase I Technical Objectives

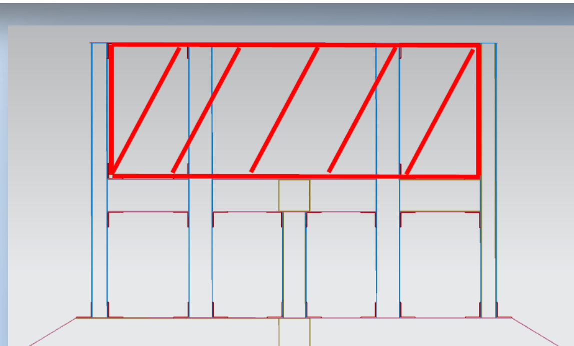
- Experimentally demonstrate full-scale, centrifugally powered actuation on modified K-MAX blade
  - K-MAX whirl rig at Kaman
  - First full-scale whirl test of actuation concept
  - First demonstration that differential can be used for actuation
- Demonstrate miniature pneumatic valve operation at ~500 g's CF
- Characterize actuator's dynamic performance limits
- Compare performance to existing on-blade active rotor technology

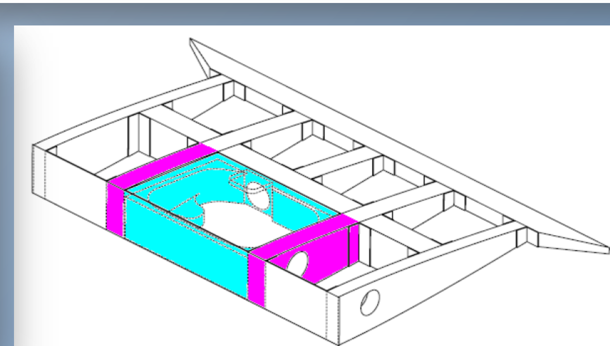
K-Max Blade Modifications

High Pressure Tube Installed in Servoflap Control Rod Volume

Low Pressure Tube Installed in Outboard Blade Section







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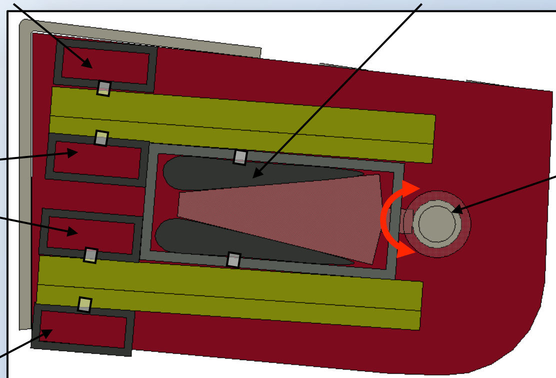
Pneumatic Actuator Design and Fabrication

Low Pressure Line

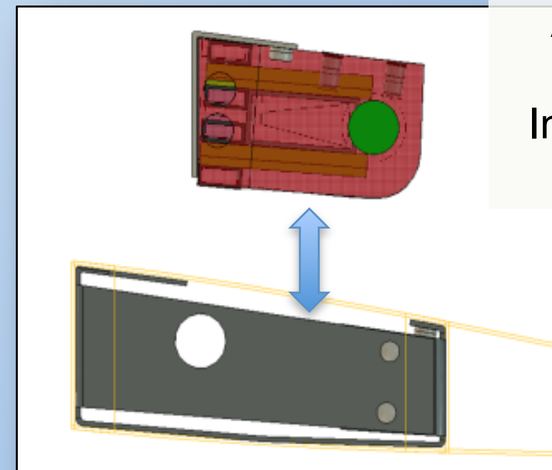
Actuating Diaphragms

High Pressure Pneumatic Lines



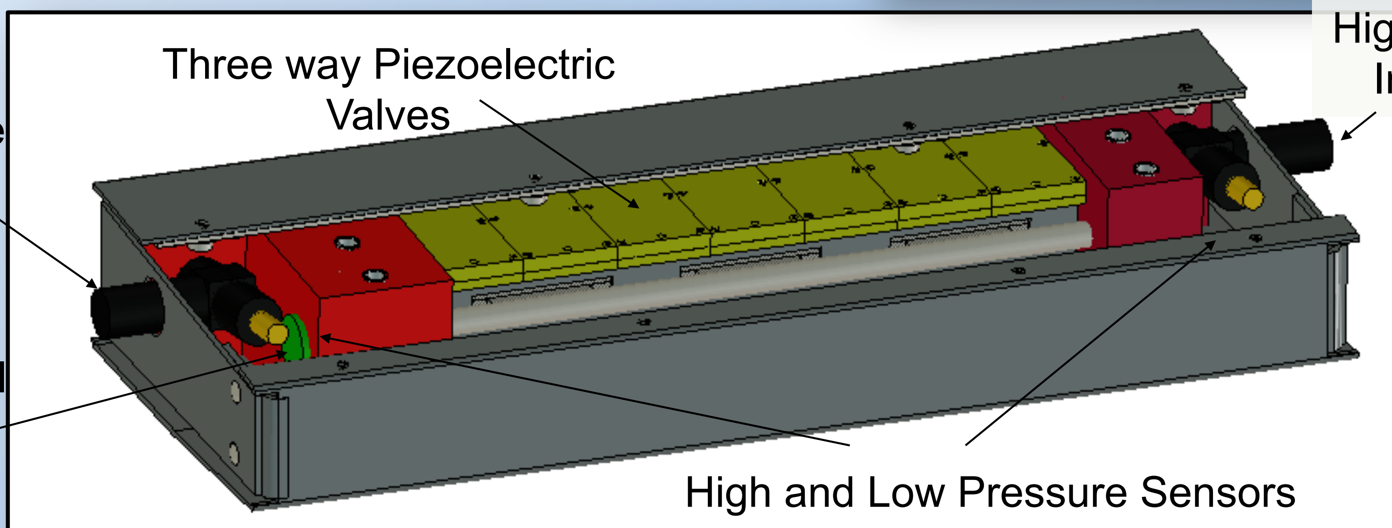
Variable Stiffness Torque Rod

Low Pressure Line



Actuator Readily Installed in Housing

Low Pressure Exhaust Line



High Pressure Input Line

Rotational Output Sensor

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Pneumatic Actuator Design and Fabrication

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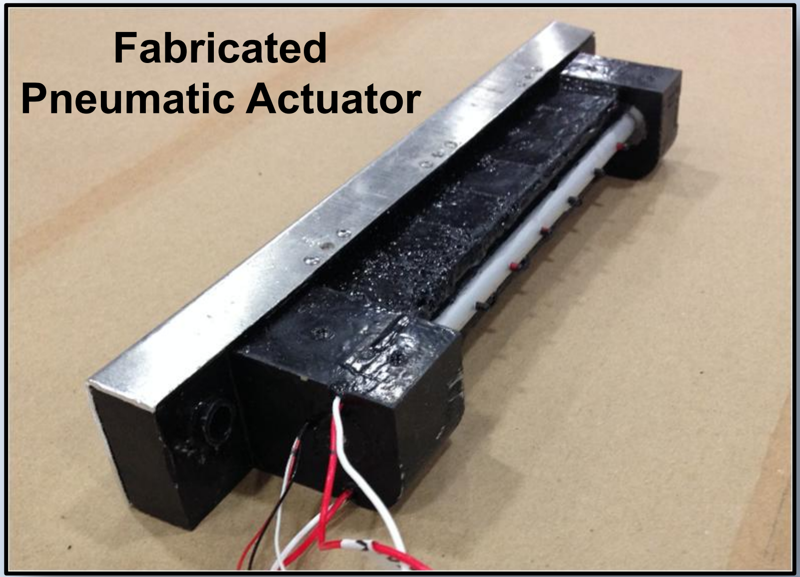

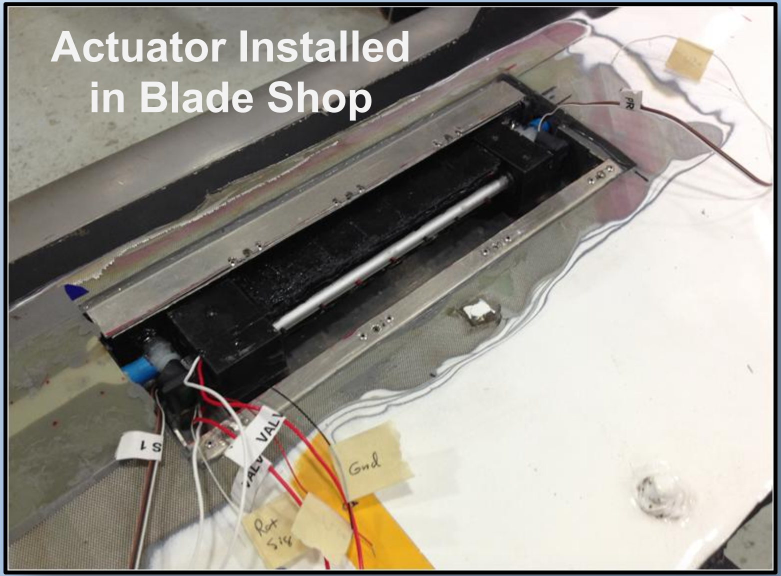

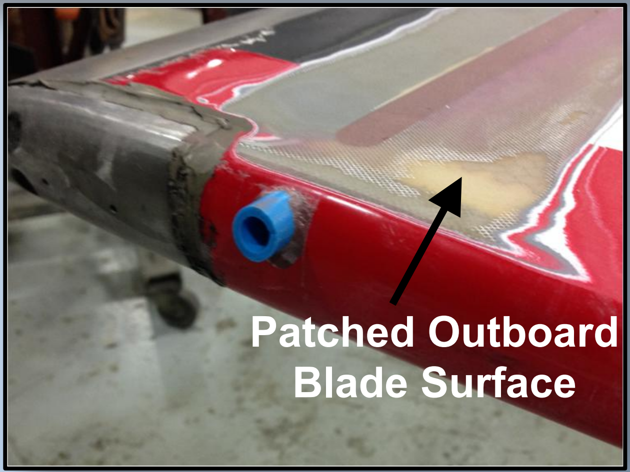

Piezoelectric Valve Design, Fabrication and Testing

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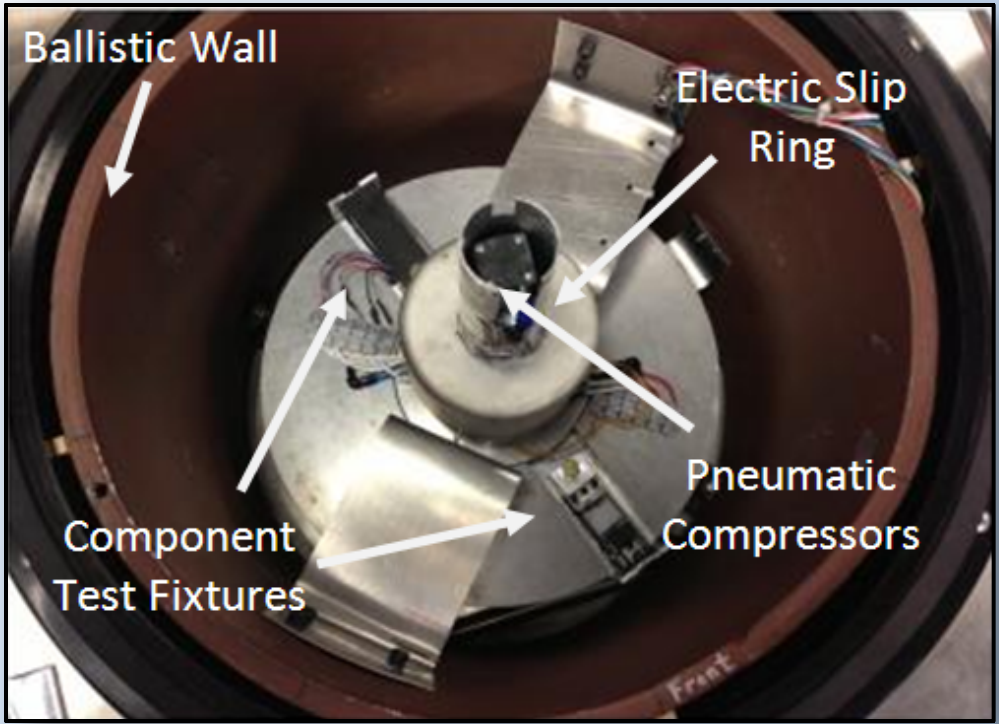
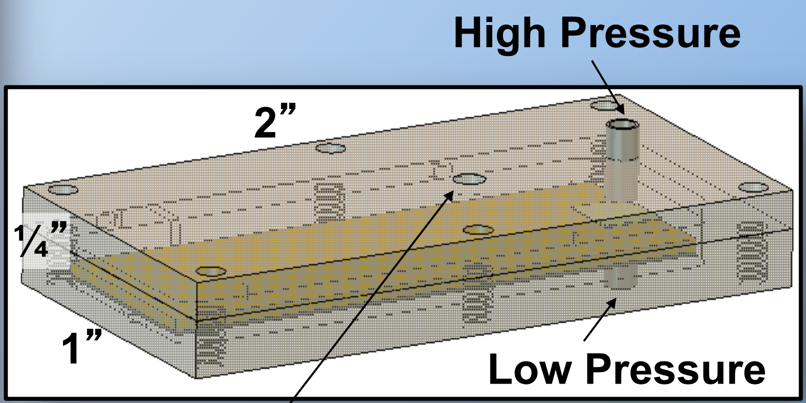


Three-way Piezoelectric Valve Fabricated at Invercon



- **Piezoelectric Valves Designed, Fabricated, and Tested at Invercon**
- **Tested in Modified Centrifuge Test Stand**
- **Successful Valve Operation Observed up to 500 g's**

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Actuator Spin Testing, October 4, 2013

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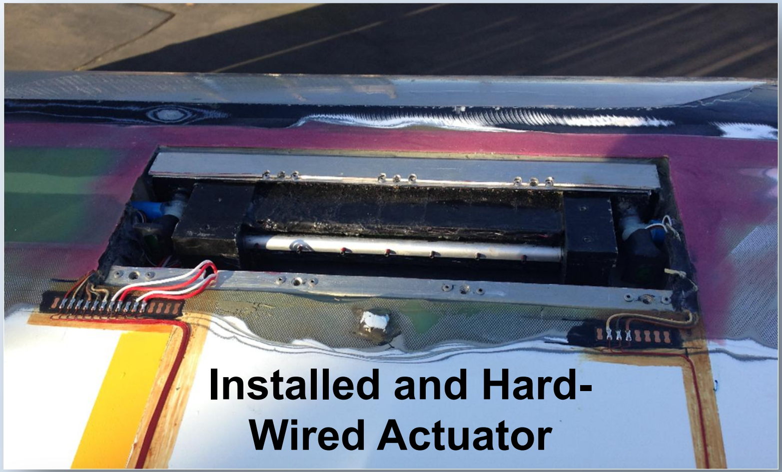
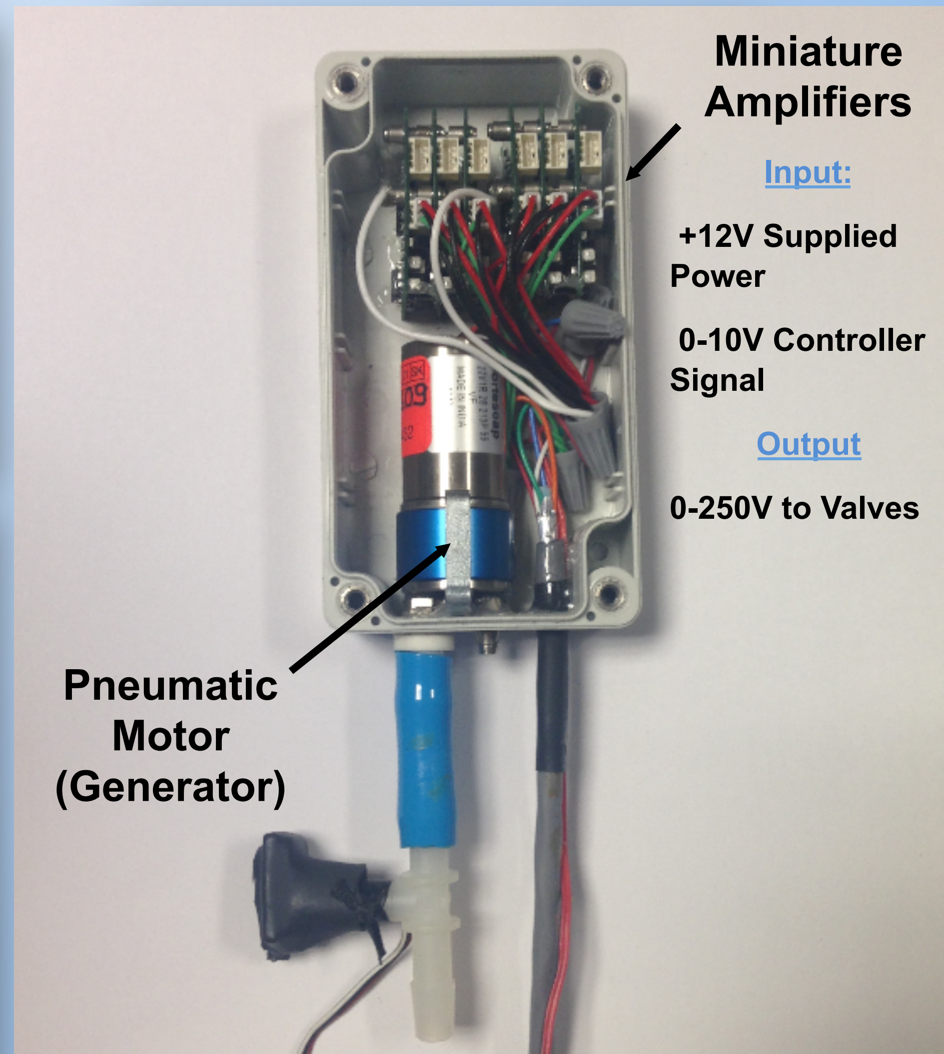
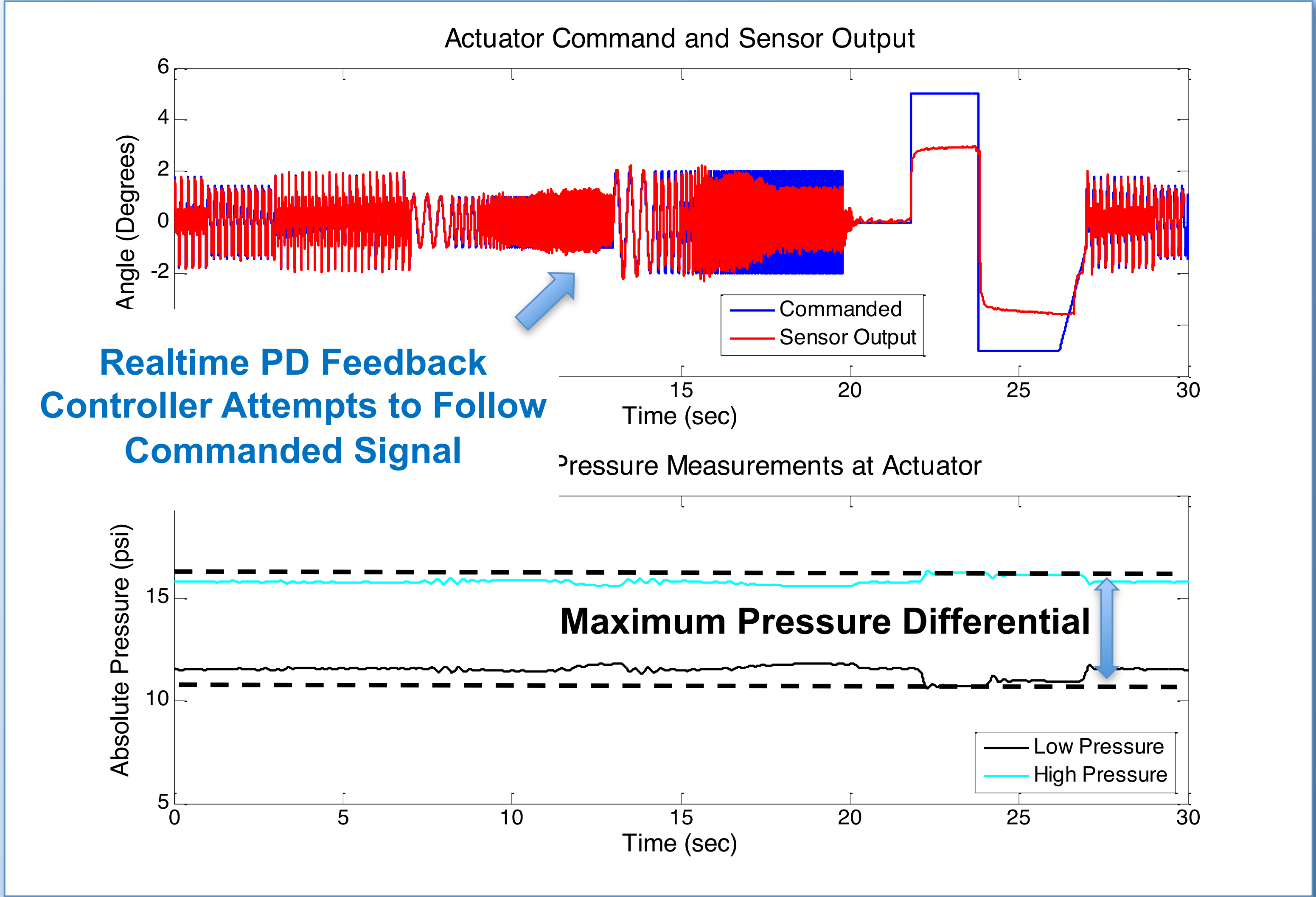




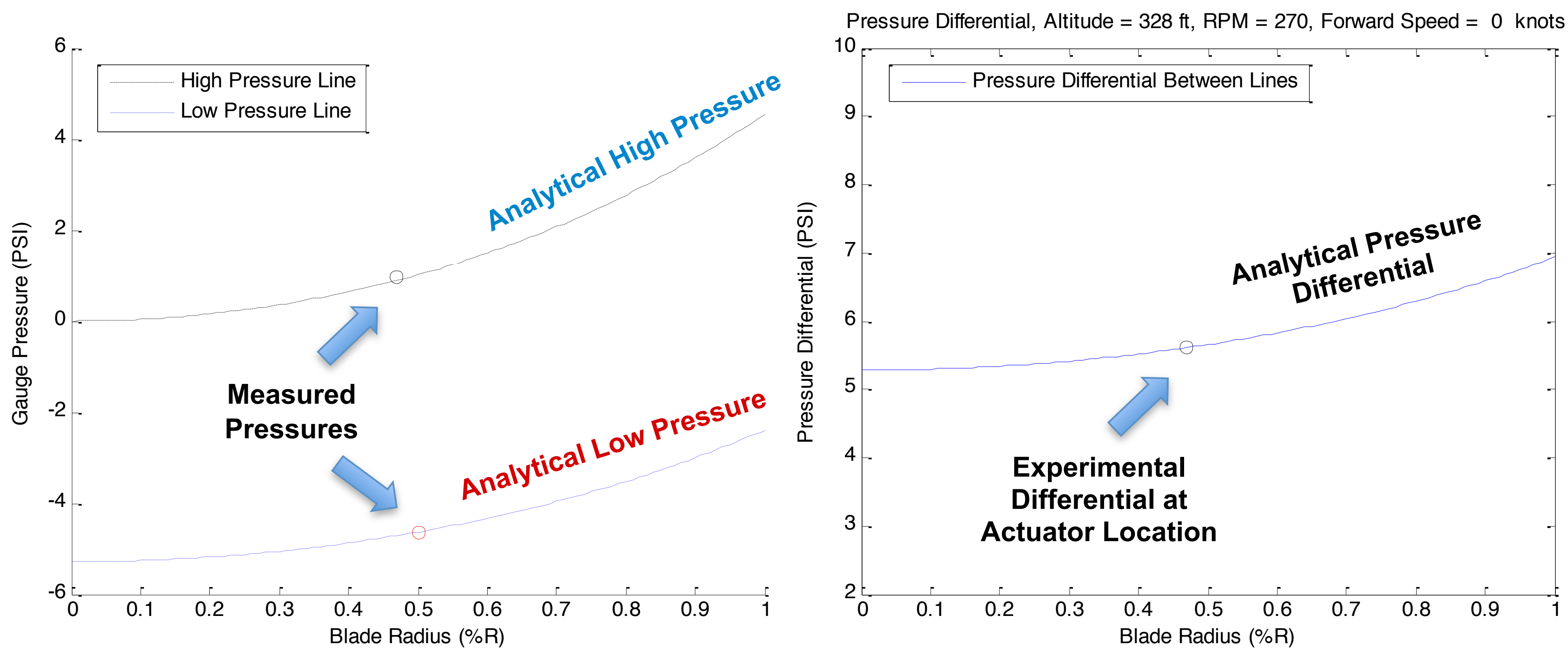
Actuator Spin Testing, October 4, 2013

Actuator Spin Testing Results



Actuator Spin Testing Results

NASA Aeronautics Research Institute



Actuator Spin Testing Results

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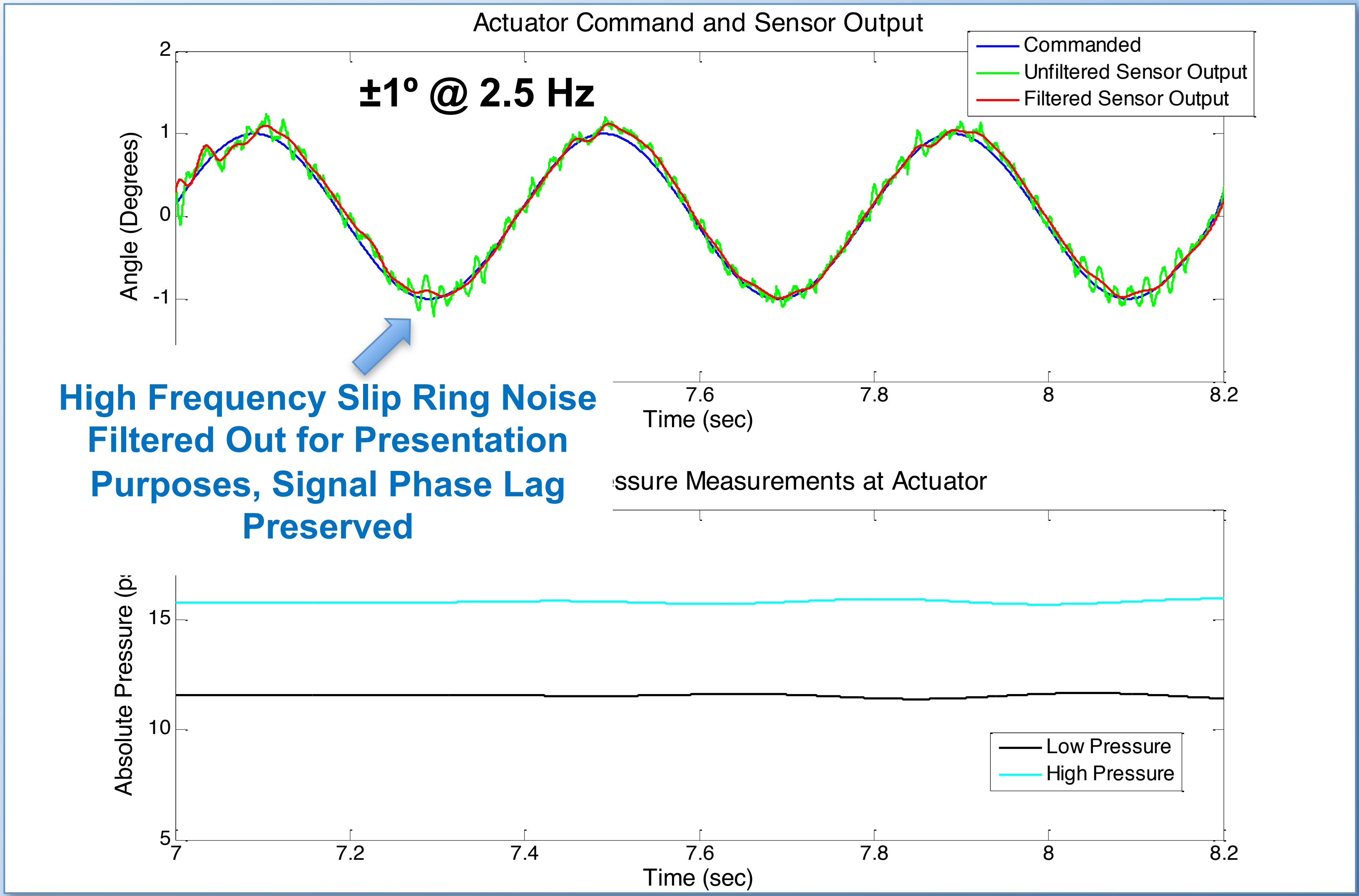

Actuator Spin Testing Results

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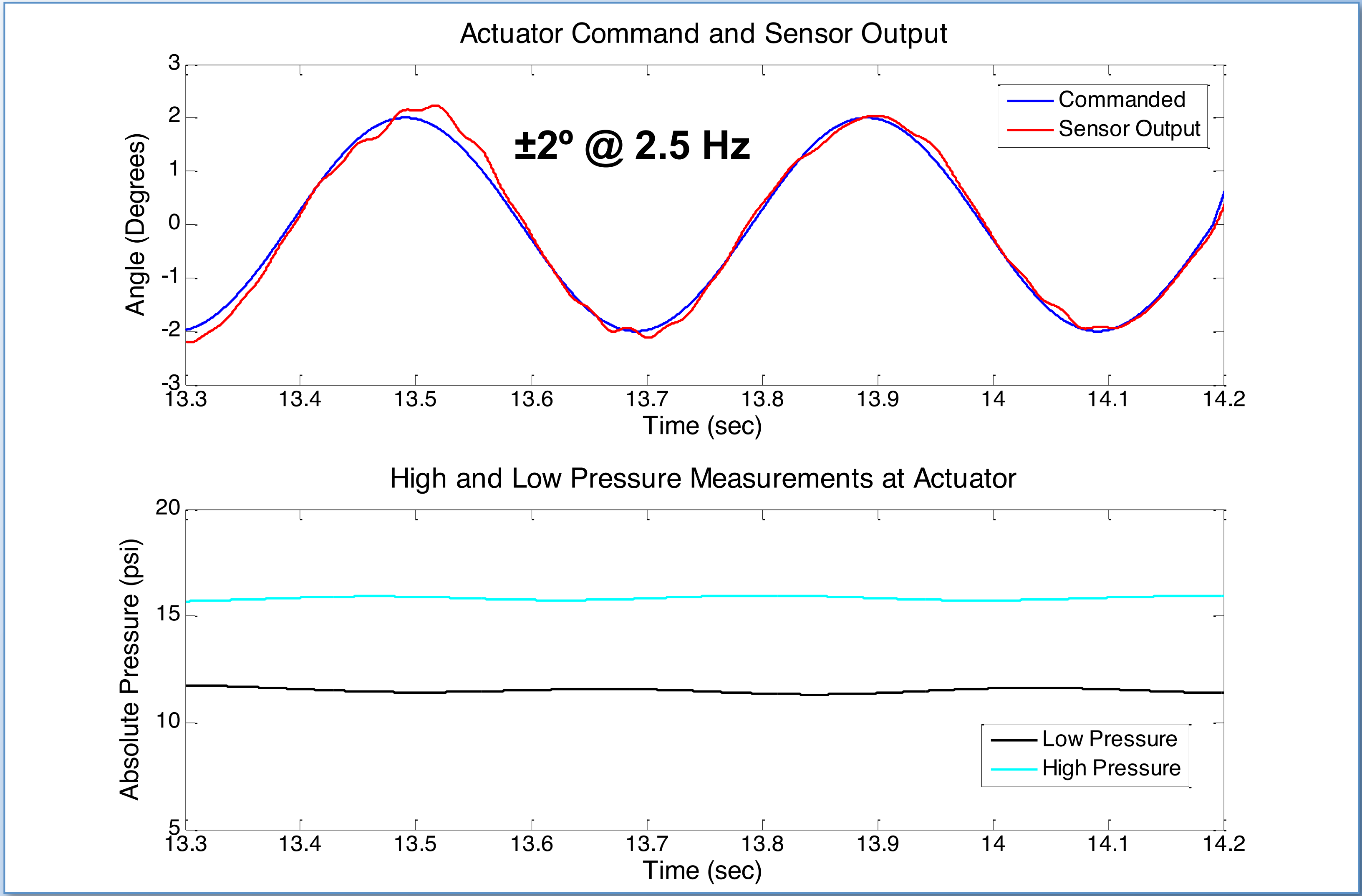

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Actuator Spin Testing Results

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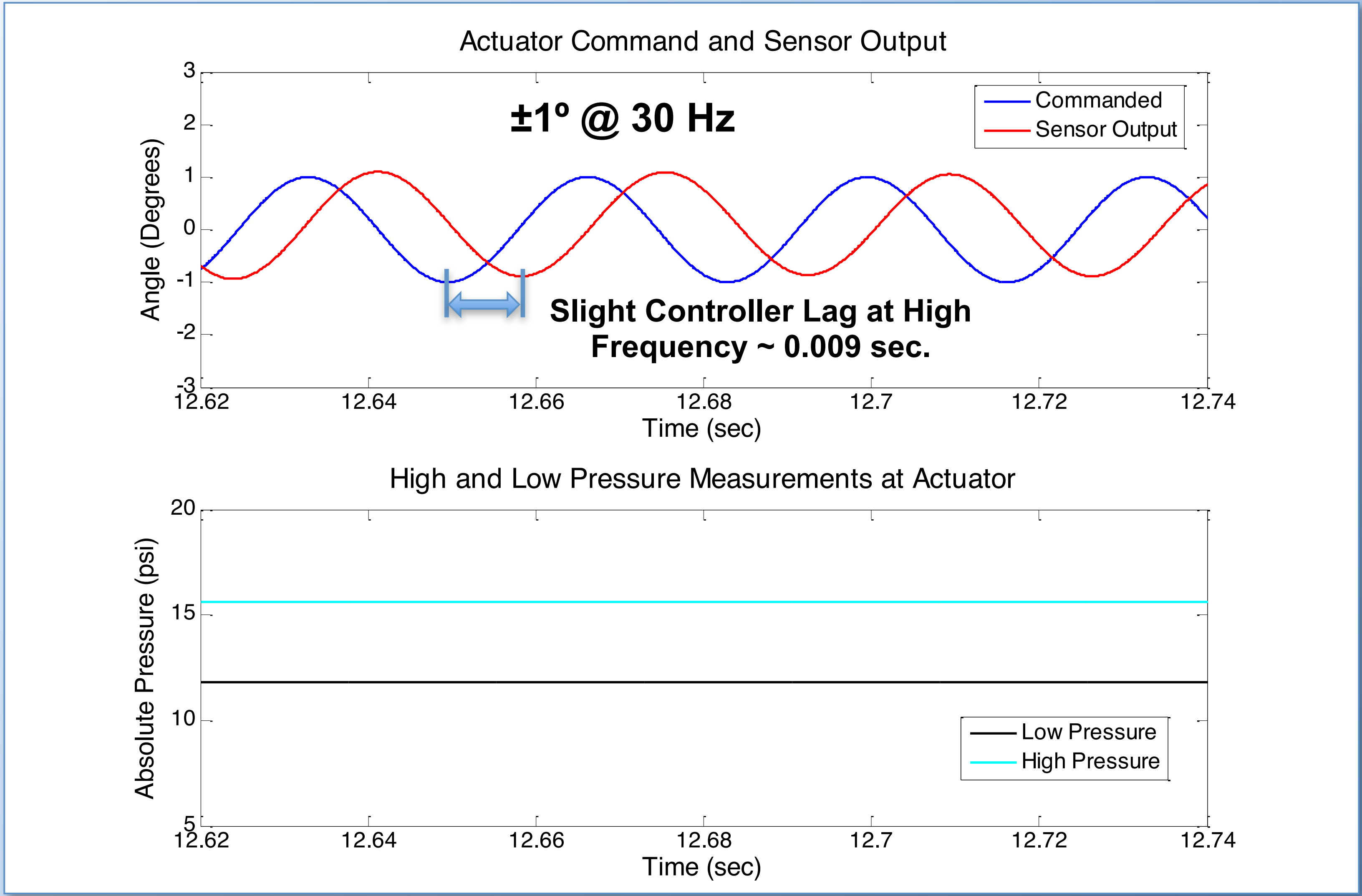

Actuator Spin Testing Results

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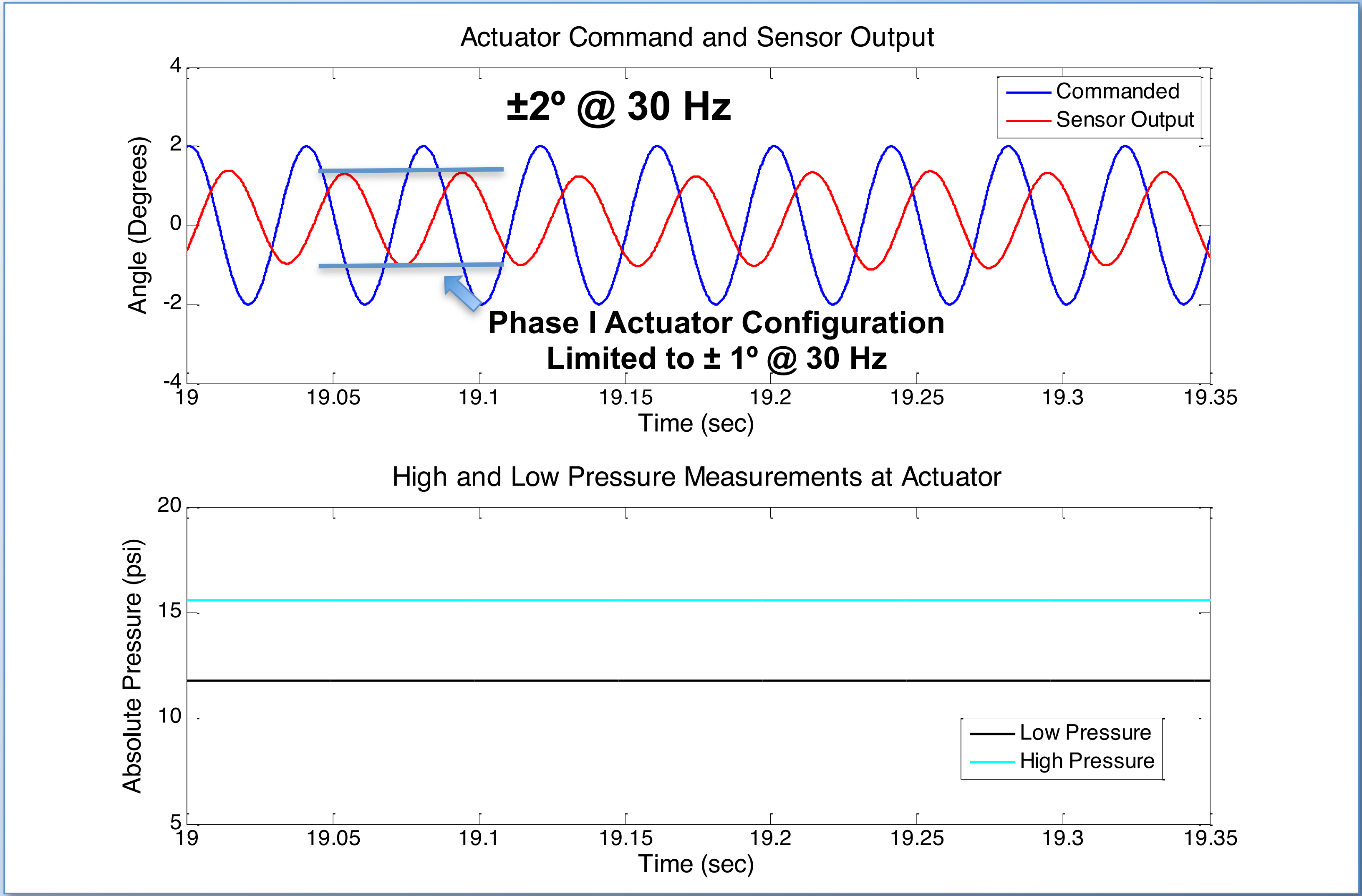
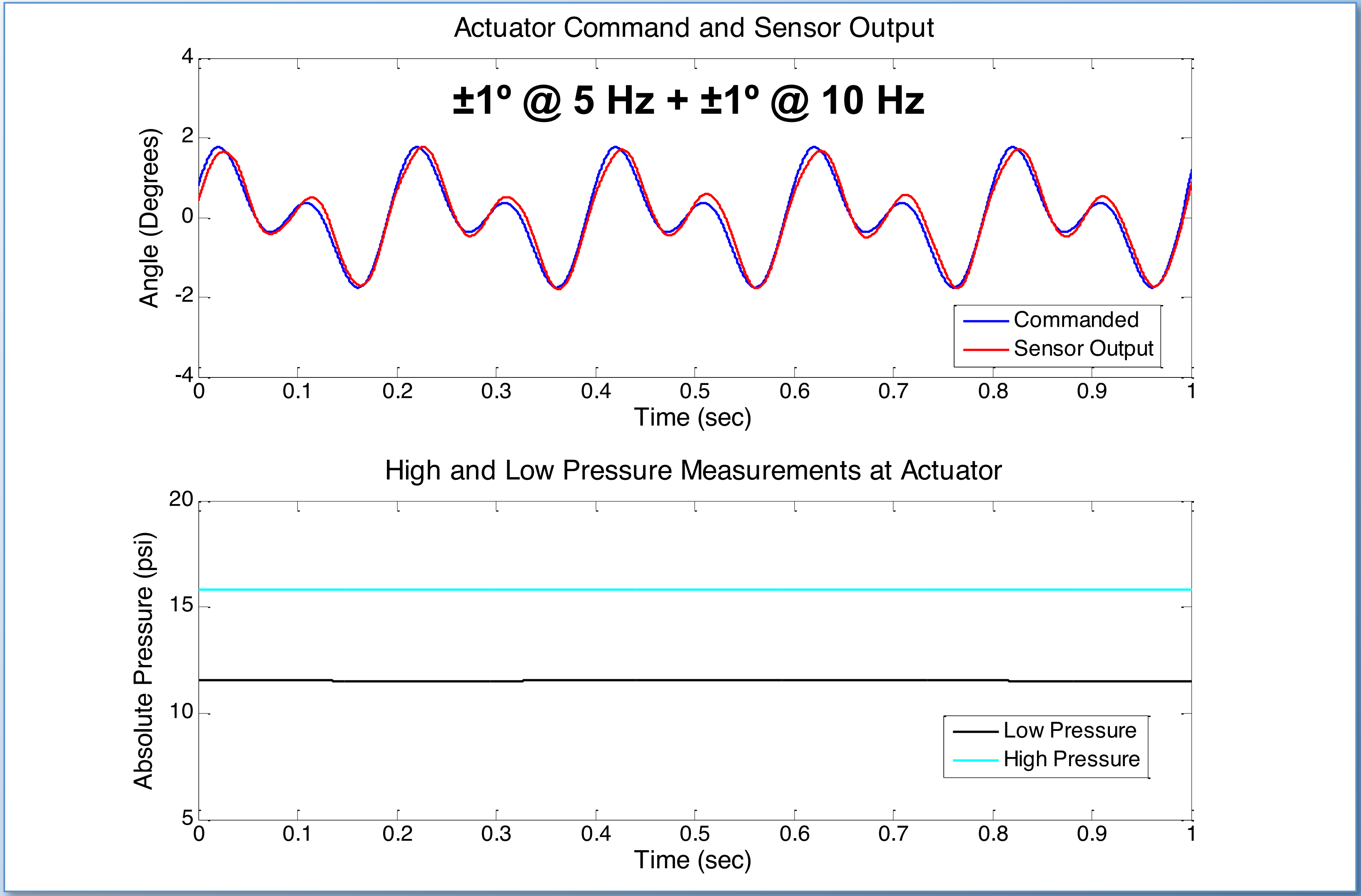


Actuator Spin Testing Results



Actuator Spin Testing Results

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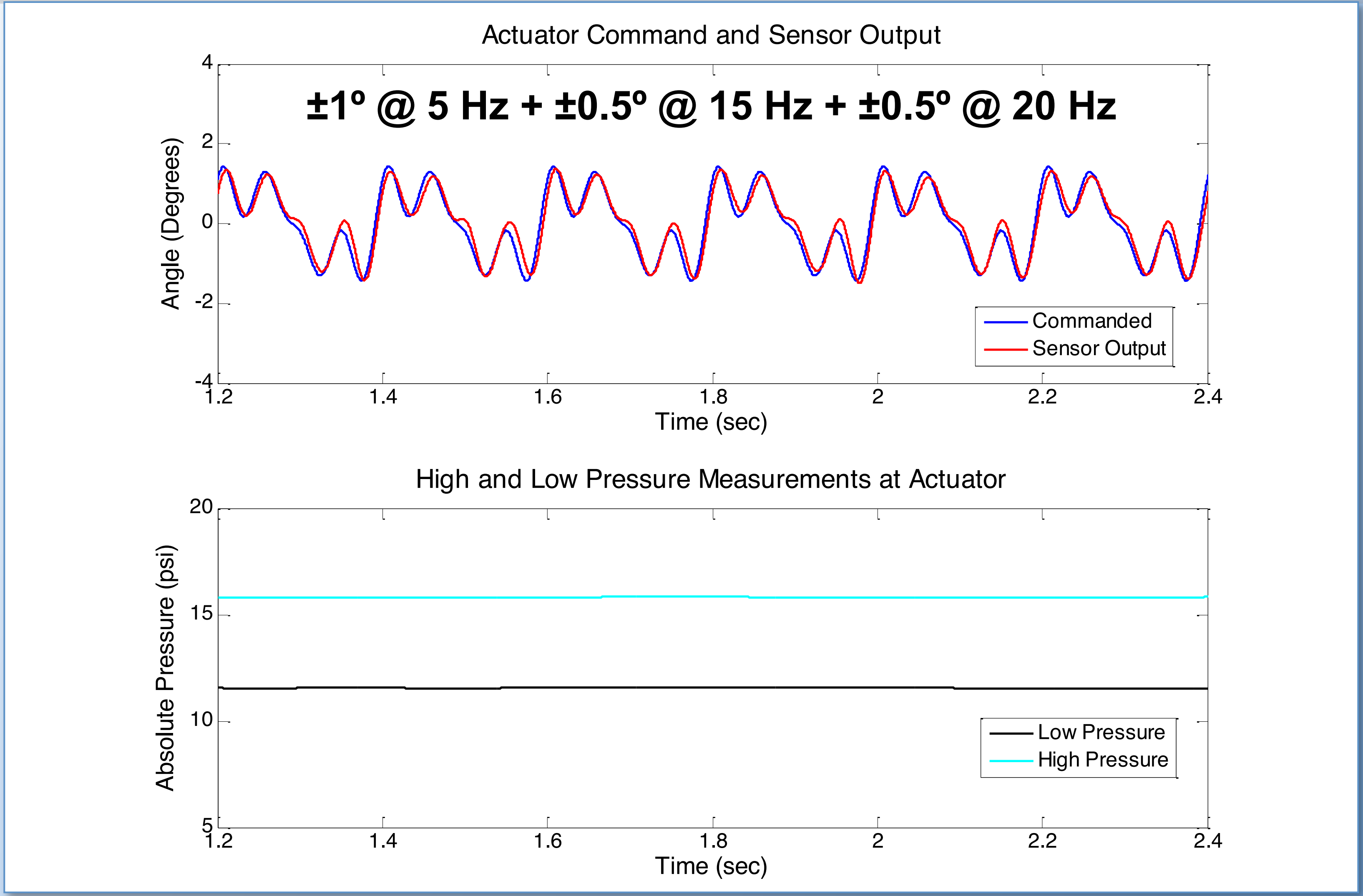

Actuator Spin Testing Results

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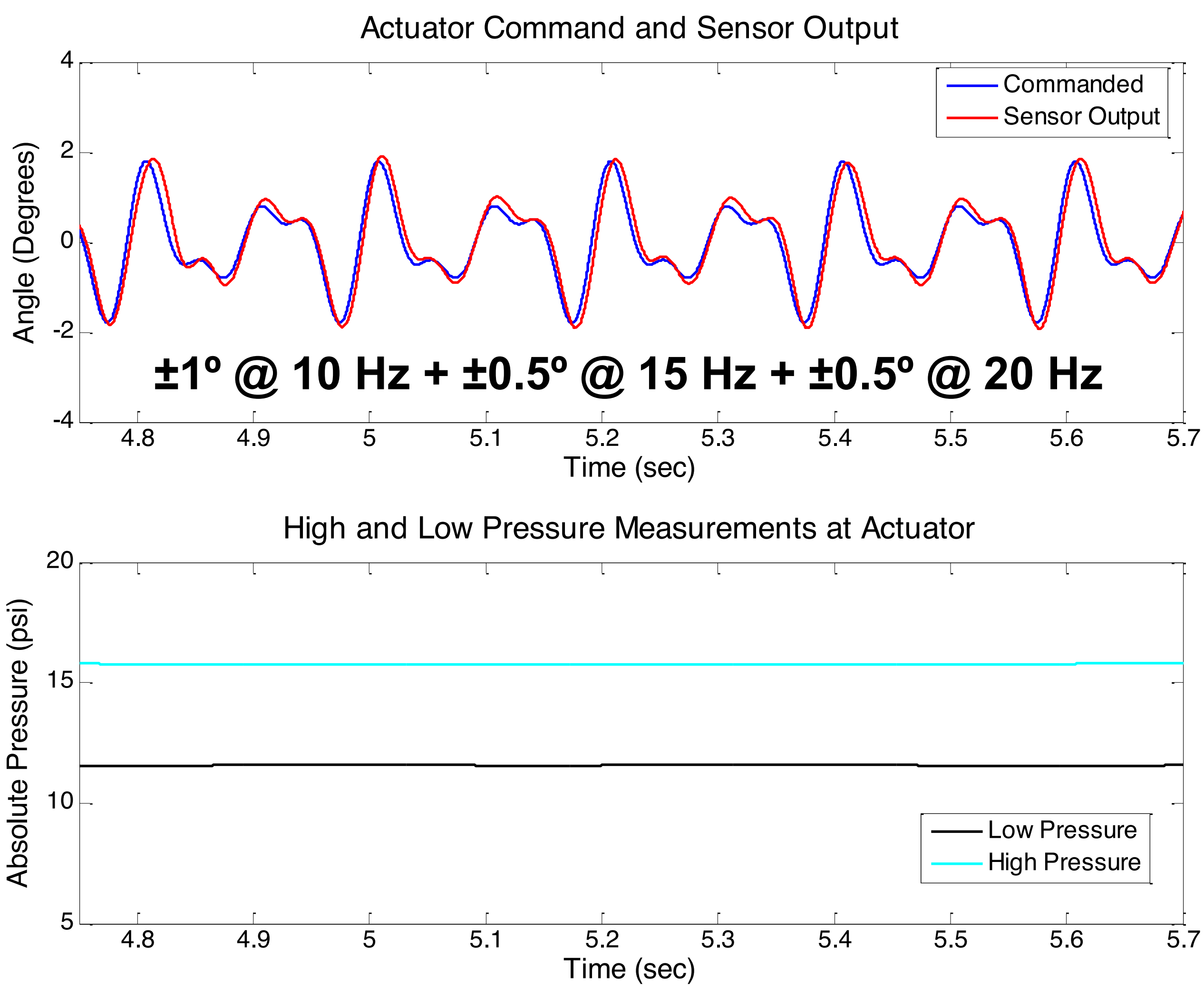

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Actuator Performance Testing

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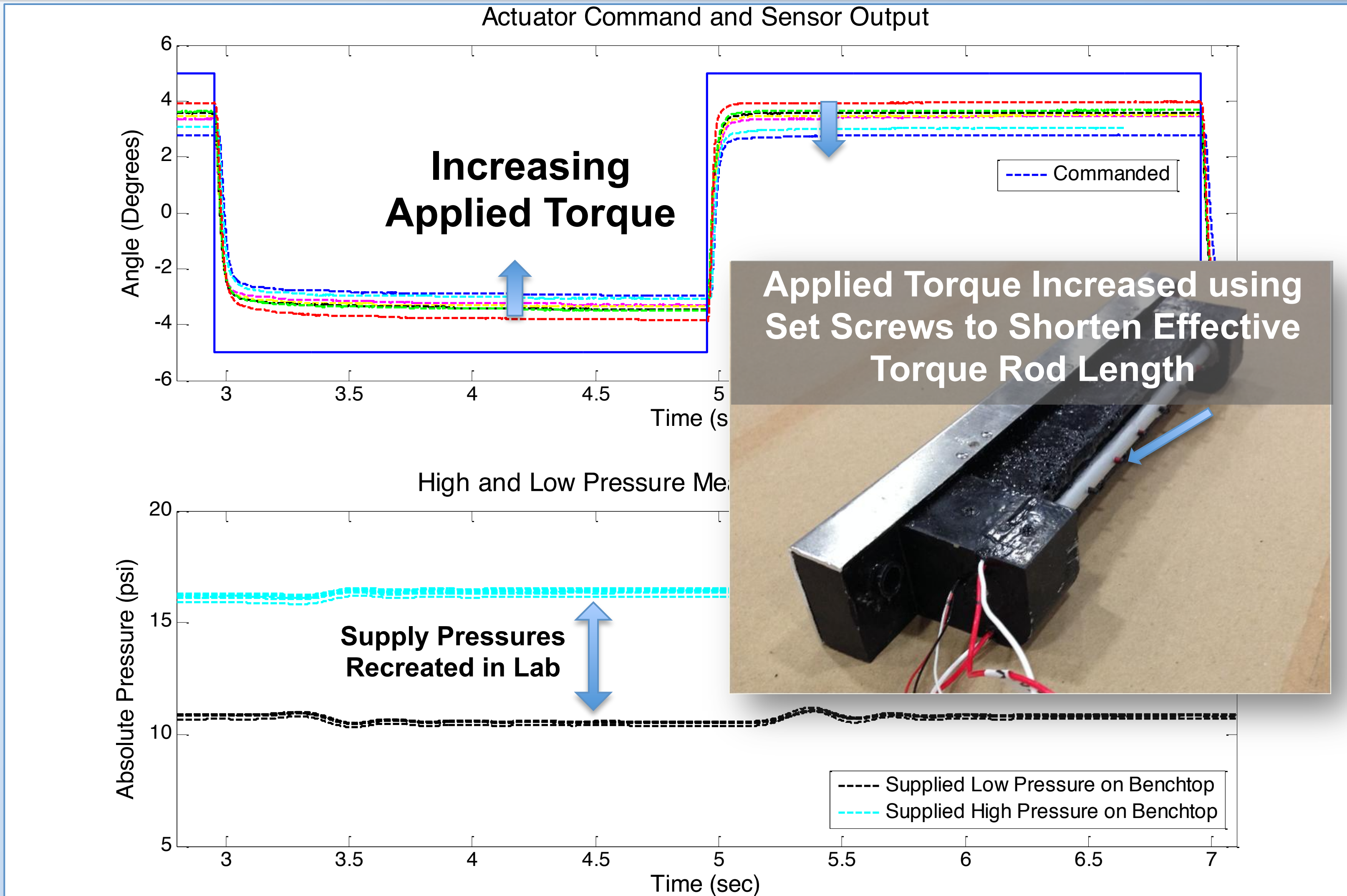
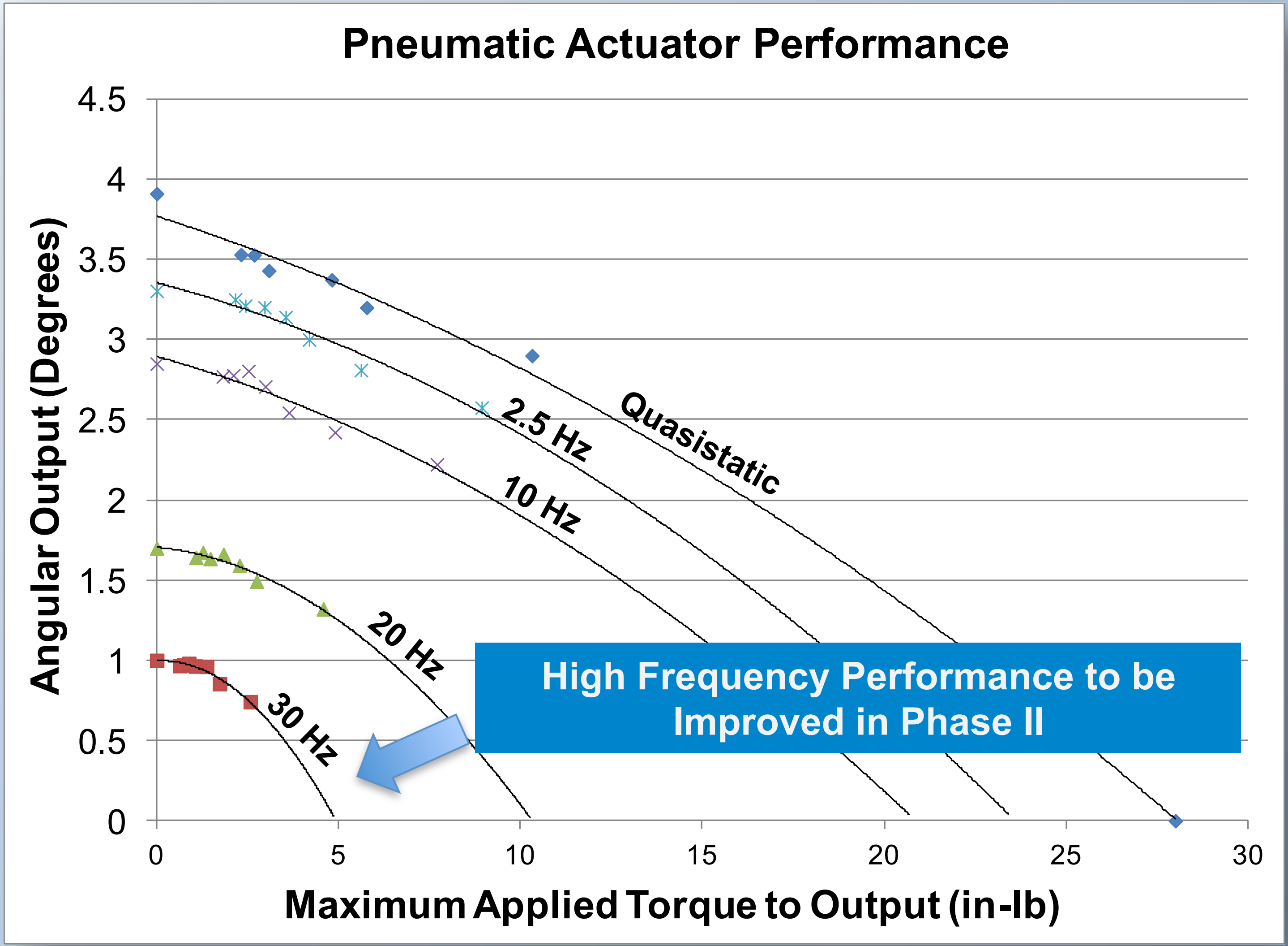


Actuator Performance Testing



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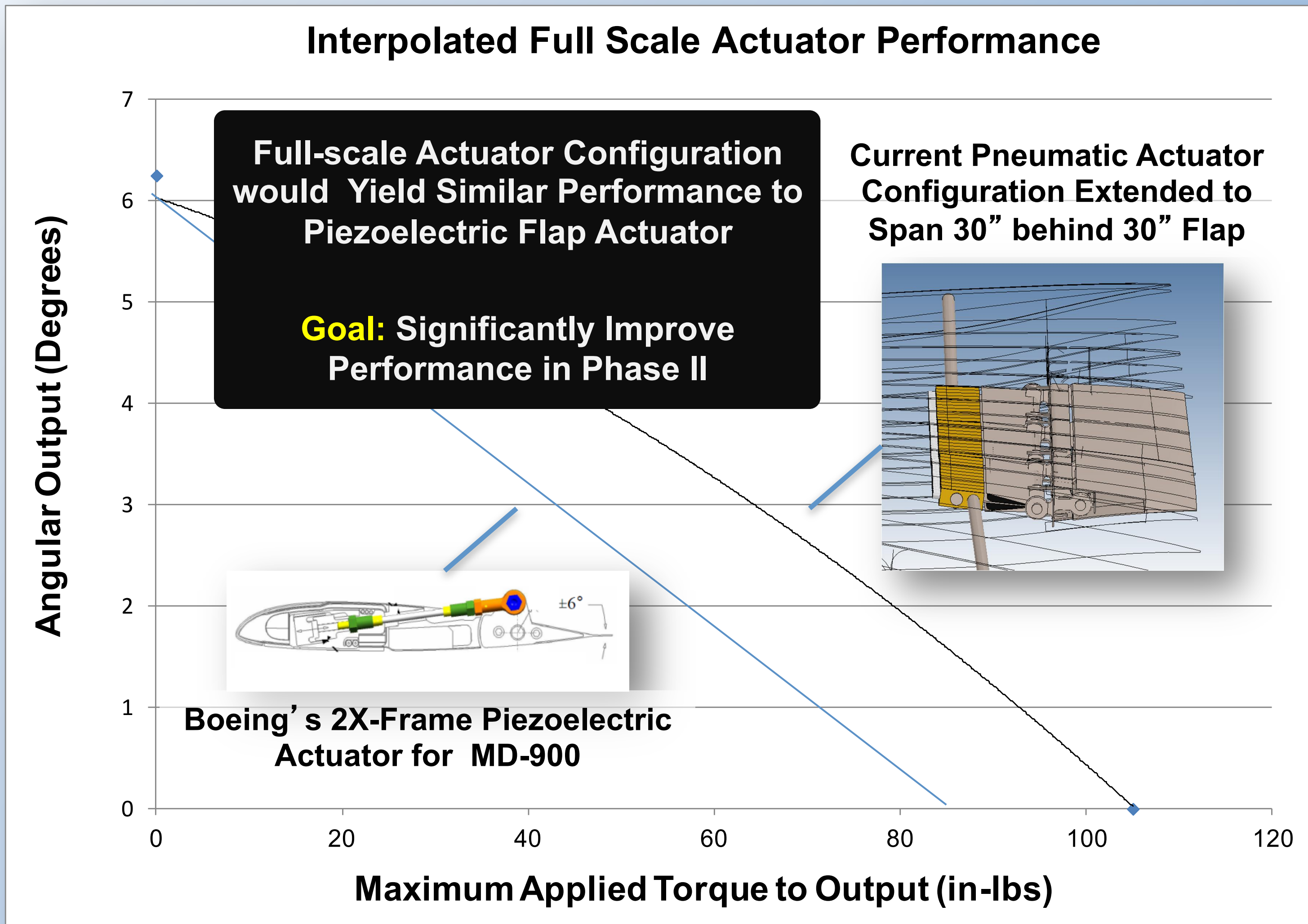
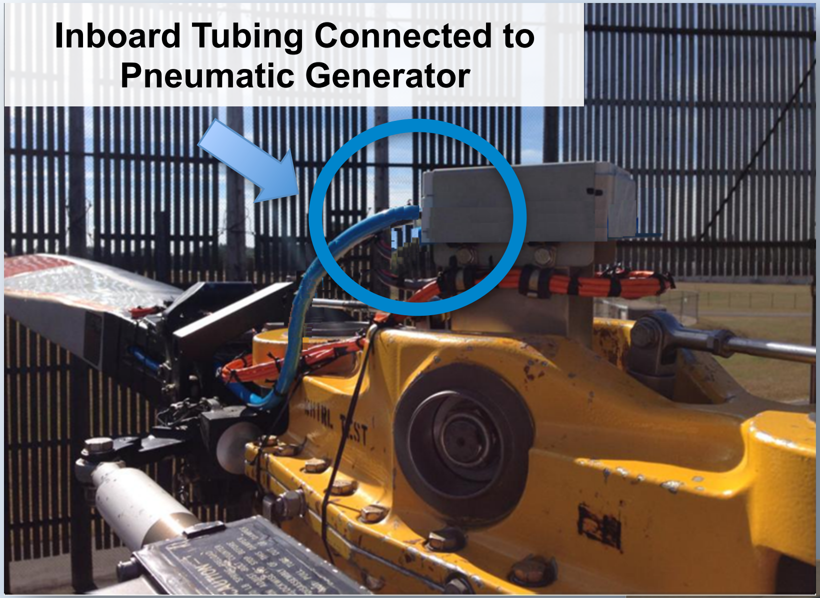
Actuator Performance Testing



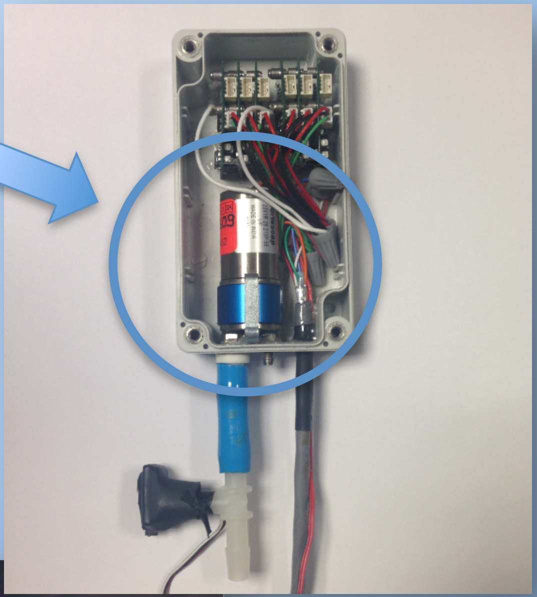
Pneumatic Power Harvesting



Inboard Tubing Connected to Pneumatic Generator

Pneumatic Rotary Vane Generator:

Diameter = 0.86”
Length = 2.4”
Weight = 120 g



Tubing Reconfigured within Housing to Bypass Actuator, Resulting in Open Tubing Entire Length of Blade

Pneumatic Power Harvesting

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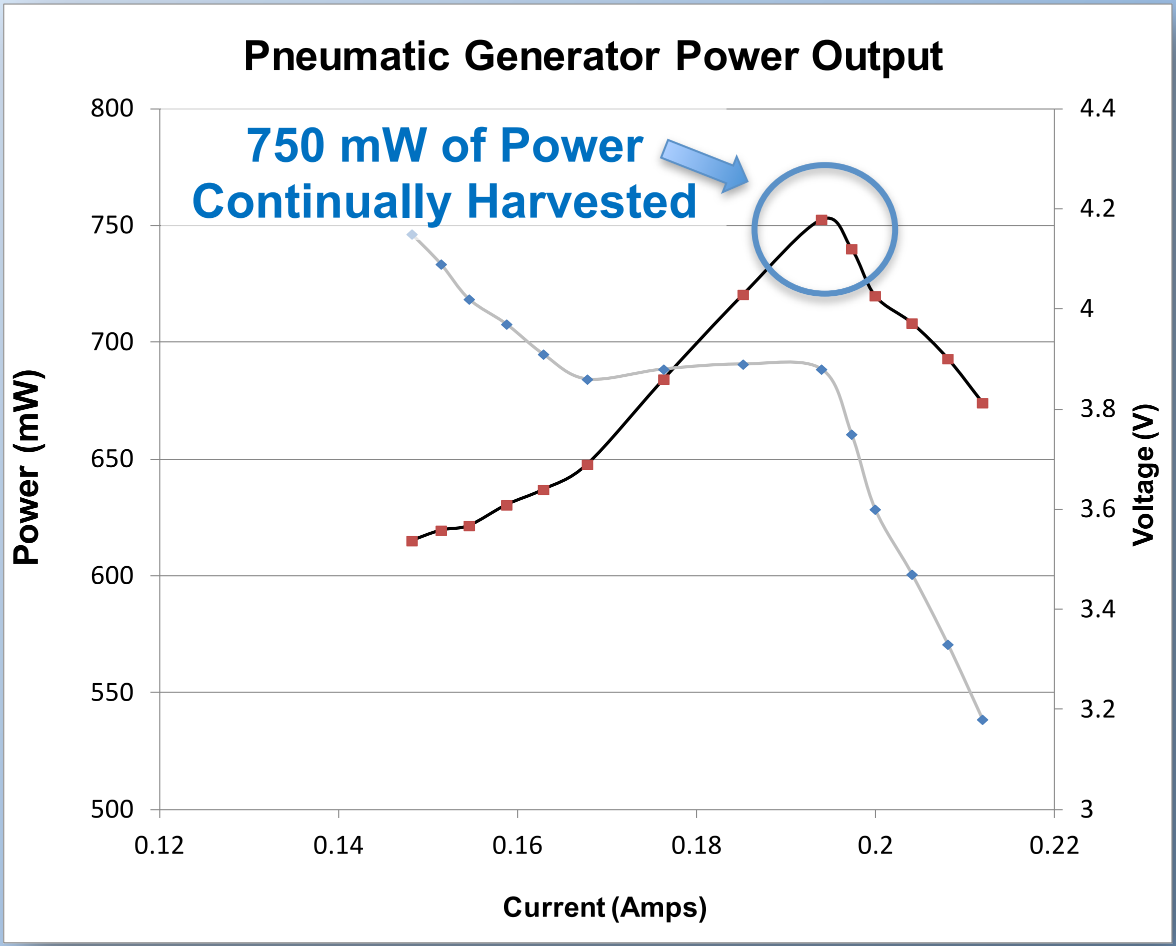
- Variable resistor at generator output used to determine maximum electrical power output
- Maximum of 0.75 Watts can be harvested for given generator size
- Generator type/design can likely be optimized to generate higher power outputs given rotor RPM and radius (~3 Watts)



Conclusions

- **Successful experimental demonstration of a full-scale, centrifugally powered pneumatic actuator**
  - **Centrifugally generated pressures used for actuation**
  - **Piezoelectric valves operated successfully under 500 g's CF**
  - **Higher frequency and multi-frequency control system demonstrated**
  - **Potential to outperform other on-blade actuation designs**
  - **Very low complexity, low weight, low power actuation solution**
- **Experimental demonstration of centrifugal power harvesting**
  - **In current full-scale test, 750 mW could be continually harvested**
  - **Sufficient power to run actuator micro-valves**
  - **Invercon will build on technologies demonstrated in Phase I**

Phase II Goal : Self-powered, wirelessly controlled, centrifugally powered actuator that requires no slip ring

Dissemination / Distribution

- Paper abstract submitted to American Helicopter Society's Annual Technical Forum

- Invercon currently working Sikorsky on related NASA NFAC wind tunnel test in 2014
  - Pneumatic MiTEs
  - Small transverse surface actuation, not flap actuation
  - Sikorsky active rotor team briefed on project progress

- Invercon currently in talks to license pneumatic flap actuator technology to Bell Helicopter
  - Bell interested in incorporating pneumatic diaphragm technology in future active rotor vehicles
  - Advocates of Invercon's proposed Phase II work

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Future Work: Self-powered, Wirelessly Controlled Actuation System for Rotorcraft

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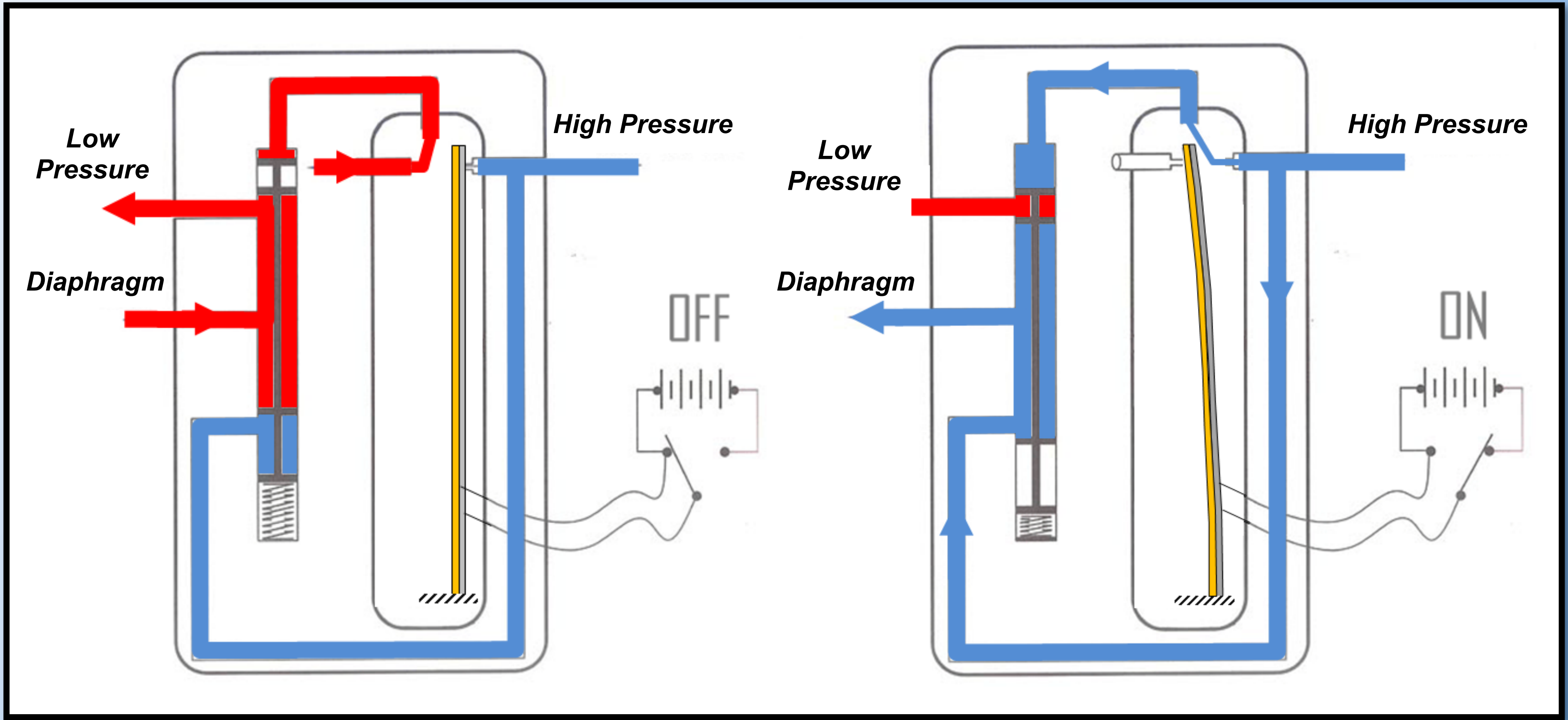
- Improve actuator high frequency performance
- Introduce piloted valve design for flow amplification



Future Work: Self-powered, Wirelessly Controlled Actuation System for Rotorcraft

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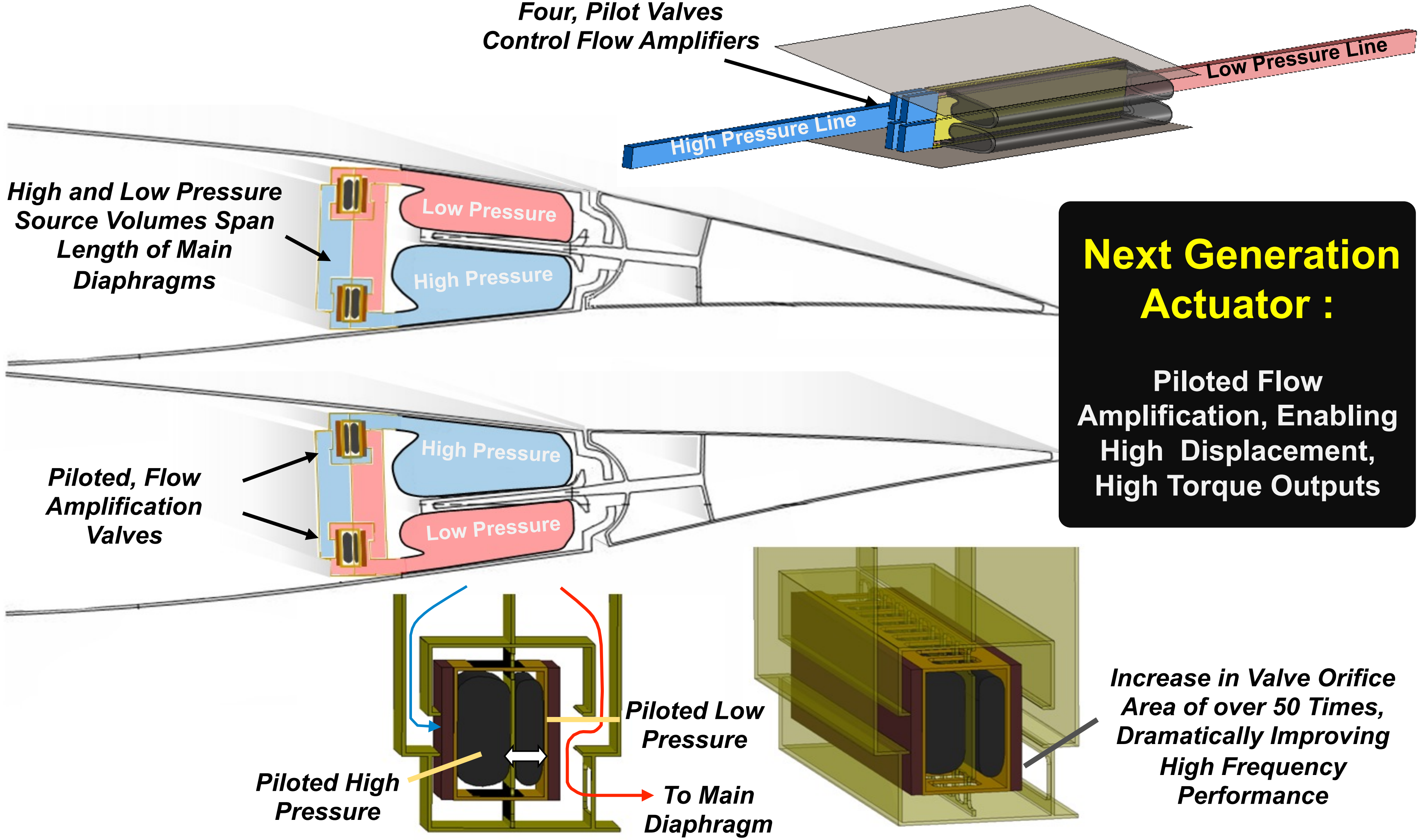

Next Generation Actuator :

Piloted Flow Amplification, Enabling High Displacement, High Torque Outputs

Future Work: Self-powered, Wirelessly Controlled Actuation System for Rotorcraft

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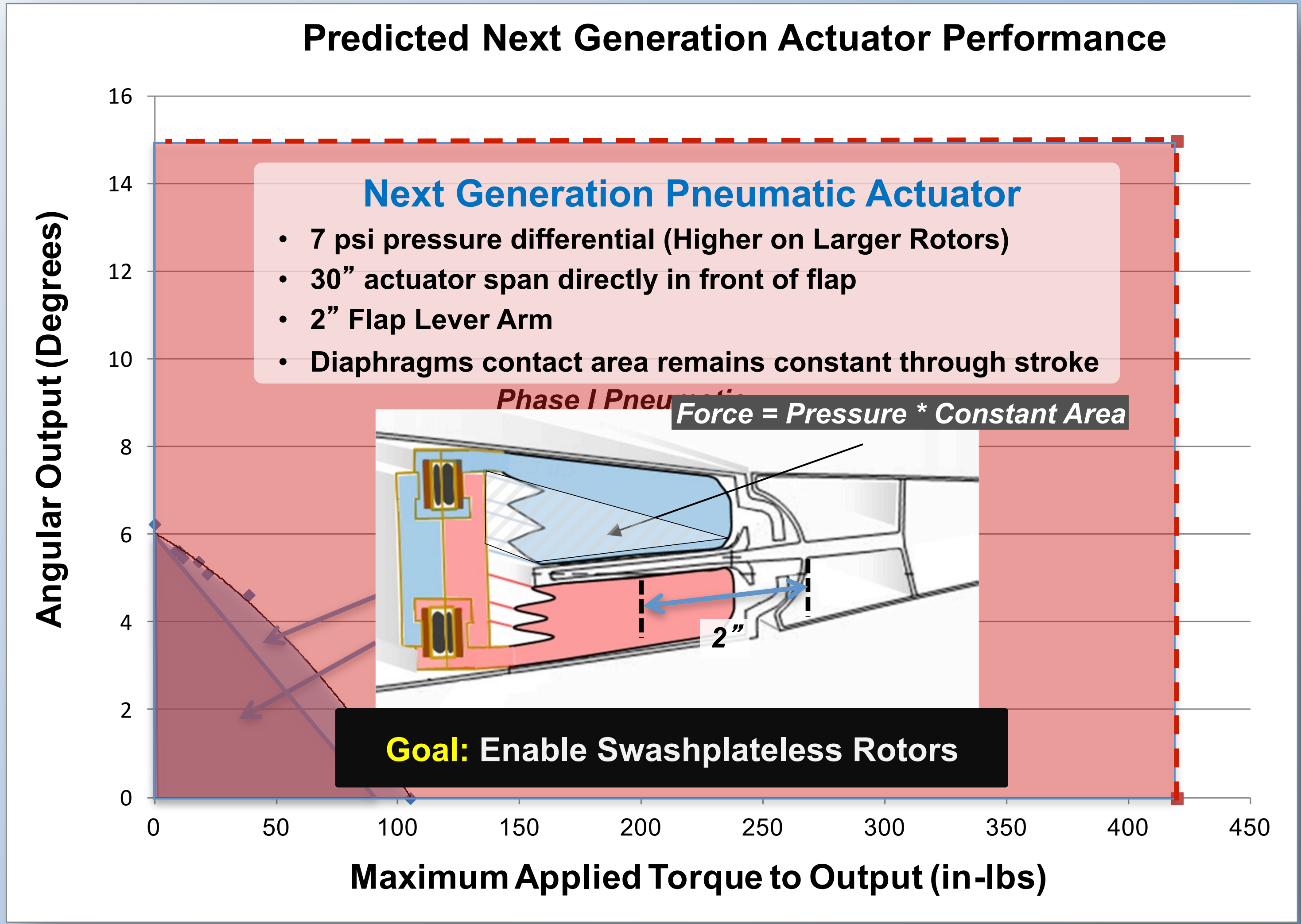
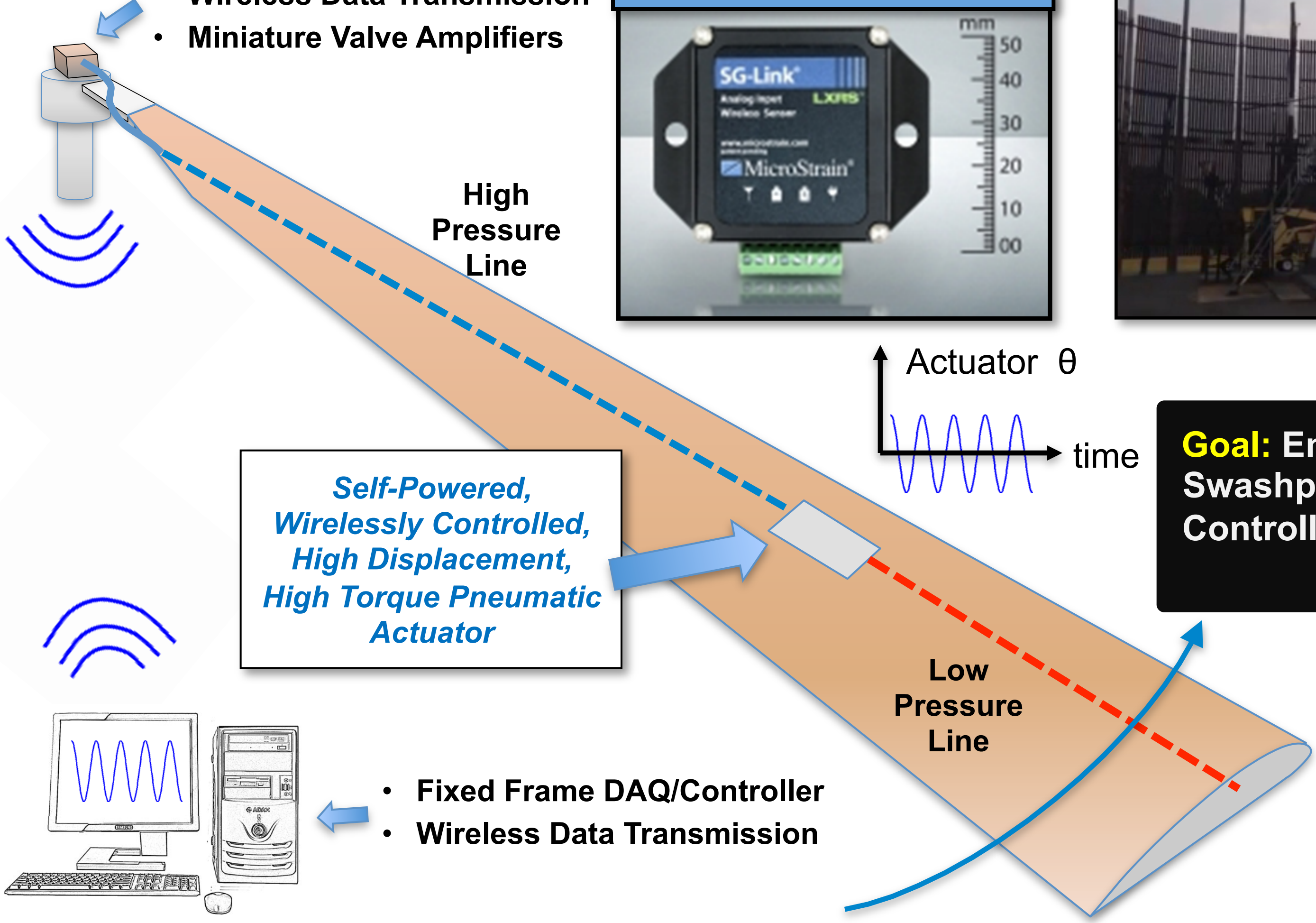


Future Work: Self-powered, Wirelessly Controlled Actuation System for Rotorcraft

- Self Powered System
- Wireless Data Transmission
- Miniature Valve Amplifiers

Off-the-Shelf Real Time Wireless Hubs



Self-Powered, Wirelessly Controlled, High Displacement, High Torque Pneumatic Actuator

- Fixed Frame DAQ/Controller
- Wireless Data Transmission

Planned Phase II Whirl Test

Goal: Enable Self-Powered, Swashplateless, Wirelessly Controlled Active Rotors of the Future

Full-scale Experimental Validation of Dynamic, Centrifugally Powered, Pneumatic Actuators for Active Rotor Blade Surfaces

Questions?